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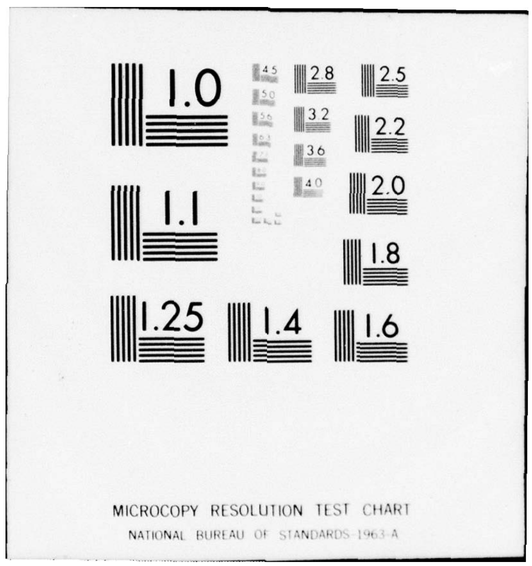
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UPDATE TO RELIABILITY AND MAINTAINABILITY PLANNING GUIDE FOR ARMY AVIATION SYSTEMS AND COMPONENTS

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August 1976

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Prepared for

U.S. ARMY AVIATION SYSTEMS COMMAND

R&M Division, Product Assurance Directorate

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This guidebook has been prepared to serve as a tool for the R&M Division of AVSCOM and for Program Managers to use in planning, managing and monitoring R&M programs for aviation systems.

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Included in the guidebook are basic concepts, program provisions, guidelines, recommendations and specific R&M plans and procedures.

The various provisions presented in this guidebook were formulated to meet the specific mission needs of AVSCOM's R&M Division, and are planned for use in support of the acquisition, operation and maintenance of Army aircraft systems and components. The major thrust of the guidebook is directed toward activities that take place during system development and production. Emphasis has been placed on mechanical reliability prediction, reliability growth testing, fault-tree analysis, and production reliability assurance techniques with specific examples applicable to helicopter systems.

Also included are maintainability and maintenance engineering topics with emphasis on state of the art diagnostics and repair philosophies and their impact on increased maintainability of helicopter systems. The compatability of existing maintainability prediction procedures with new maintenance philosophies is discussed. Discussions are included on other evaluation techniques which emphasize maintainability verification, demonstration and evaluation. The concept of availability is established and means for its improvement discussed in the context of reliability and maintainability controls. The concept of warranty and its impact on R&M improvement has been introduced in the final section of the guidebook.

The appendices contain sample operating procedures which show how concepts given in the earlier part of the guidebook may be applied to typical helicopter program situations. Included are abstracts of current documentation on Life Cycle Cost, and Reliability Improvement Warranties. A reduced flow chart of Army management activities during major system procurement is also provided.

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UPDATE TO RELIABILITY AND MAINTAINABILITY PLANNING GUIDE FOR ARMY AVIATION SYSTEMS AND COMPONENTS

R & M DIVISION DIRECTORATE FOR PRODUCT ASSURANCE
U.S.Army Aviation Systems Command

UPDATE TO RELIABILITY AND MAINTAINABILITY PLANNING GUIDE FOR ARMY AVIATION SYSTEMS AND COMPONENTS

AUGUST 1976

R & M DIVISION, DIRECTORATE FOR PRODUCT ASSURANCE
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ST. LOUIS, MISSOURI

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IIT RESEARCH INSTITUTE
CHICAGO, ILLINOIS

FOREWORD

The objective of the Army Aviation Systems Command Directorate for Product Assurance is to insure user satisfaction with its product. In the eyes of the user, the AVSCOM product is either good (reliable) or marginal (a problem to maintain and support). In order to guarantee the quality of the product, reliability and maintainability (R&M) effort must be applied consistently throughout the entire life cycle of the system. The R&M task must begin at the earliest point in design, continue through production, and extend to follow-on maintenance and supply practices.

The purpose of this document is to establish an AVSCOM aviation system approach to R&M which is fully in accord with AMC guidelines. The AVSCOM R&M Planning Guide for Army Aviation Systems and Components will provide guidance for each Program Manager on how to integrate R&M provisions into his specific Systems Development Plan.

The individual responsible for the direction and implementation of this effort is Mr. Lewis Neri, Chief of the Reliability and Maintainability Division, Directorate for Product Assurance. Constructive criticism from users is invited and encouraged, and it is sincerely requested that such information be forwarded to Mr. Neri. Revision and updating of the planning guide are envisioned at appropriate intervals.

Edward J. Hollman

Edward J. Hollman
Director of Product Assurance

ACKNOWLEDGEMENT

This guidebook was prepared by IIT Research Institute (IITRI) under the technical direction of the R&M Division, Product Assurance Division, AMSAV-LR, AVSCOM (Contract No. DAAJ01-73-C-0912). It is intended to serve as a management guide for the R&M Division of AVSCOM and for Program Managers to use in planning, managing and monitoring R&M programs for aviation systems.

At IITRI, this project was conducted under the direction of R. T. Anderson, Manager, Reliability Section. The key technical contributor was D. W. Kos assisted by J. J. Schiller and other members of the technical staff of IITRI's Reliability Section.

On the part of the government, the project was under the technical cognizance of Mr. Lewis Neri, Chief of Reliability and Maintainability Division, Directorate for Product Assurance, U. S. Army Aviation Systems Command. Mr. Elmer Lueckerath provided valuable information concerning Army documents and regulations concerning helicopter procurement practices and management policies.

In addition, IITRI would like to acknowledge the cooperation of the Bell Helicopter Company and previous Helicopter R&M studies performed by Boeing Vertol.

In order to provide a planning guide so broad in scope, an exceptional degree of cooperation from AVSCOM and contractor personnel was required. For this cooperation, IITRI is sincerely appreciative.

Respectfully submitted,
IIT RESEARCH INSTITUTE

Ronald T. Anderson

Ronald T. Anderson
Manager, Reliability

PREFACE

This guidebook was prepared by IIT Research Institute (IITRI) under the technical direction of the R&M Division, Product Assurance Division, AMSAV-LR, AVSCOM (Contract No. DAAJ01-75-C-1094 (PIG). The document is an update to the previous publication entitled "Reliability and Maintainability Planning Guide for Army Aviation Systems and Components. The guidebook and this revision has been prepared to serve as a tool for the R&M Division of AVSCOM and for Program Managers to use in planning, managing and monitoring R&M programs for aviation systems. This update expands the scope to include maintainability and maintenance topics in detail.

The format of the updated guidebook remains much the same, consisting of five basic sections with supporting appendices. The bulk of the additional information on maintainability has been incorporated into Section 4.0. Therein, subsections have been added on basic theory establishing the foundations for maintainability prediction, allocation and assessment. Maintainability and maintenance engineering topics are presented with emphasis on state of the art diagnostics and repair philosophies and their impact on increased maintainability of helicopter systems. The compatability of existing maintainability prediction procedures with new maintenance philosophies is discussed. As well, discussions are included on other evaluation techniques which emphasize maintainability verification, demonstration and evaluation. The concept of availability is established and means for its improvement discussed in the context of reliability and maintainability controls. Finally, the concept of warranty and its impact on R&M improvement has been introduced in the final section of the updated guidebook. Also the guidebook appendices have been greatly expanded to include descriptions of the latest R&M documents and, in particular, these documents covering Maintainability and Life Cycle Cost, and Reliability Improvement Warranties.

As in the initial guidebook, the major thrust is directed towards activities which take place during system development and production. Where the inital guidebook emphasized reliability controls in the design and production phases, this update elaborates upon these tasks. Implementation of these tasks performed during early life-cycle phases dramatically improves field maintenance and reduces operating and maintenance degradation.

Submitted by;
IIT RESEARCH INSTITUTE

Peter A. Mihalkanin
Project Engineer

APPROVED:

R. T. Anderson
Manager
Reliability Section

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Section 1.0

INTRODUCTION

Section 1.0

INTRODUCTION

1.1 Purpose and Scope of Guide

This document has been prepared for the Reliability and Maintainability (R&M) division of the Army Aviation Systems Command (AVSCOM), to serve as a management guide, and is applicable to all Army aviation systems and components. The R&M division, as it functions within AVSCOM's product assurance directorate, is responsible for planning and developing life cycle R&M programs, managing and evaluating contractor efforts and, in general, providing technical support to project managers in the technical review of contractor R&M efforts. Meeting this responsibility requires work efforts that are integrated into the total system development and which cover all life cycle phases including pre-procurement, procurement and post-procurement activities. This document, therefore, provides specific guidelines for planning work efforts, allocating resources, and evaluating and reporting all significant life cycle R&M activities.

In addition, this guidebook provides a tool for implementing the general policies of the Army for R&M as called out in Army Regulation 702-3 and proposed revisions. It sets forth improved methods for organizing and implementing R&M activities and provides a framework which embodies a preventive rather than a corrective approach to R&M.

The guidebook recognizes that R&M are critical variables in the procurement of complex Army aviation systems and components because of their significant impact on:

(1) Flight safety (catastrophic failure) including both personnel injury and aircraft loss.

(2) Mission success (mission reliability) such as mission aborts or an inability to fulfill the complete requirements of the mission.

(3) Unscheduled maintenance (System Reliability) factors such as maintenance costs and system effectiveness throughout its life cycle.

This book is intended to provide R&M guidelines in relationship to these safety, mission, maintenance and cost factors which together form the elements for system engineering and cost effectiveness. However, it does not cover system engineering or cost effectiveness themselves. Instead, it assumes an awareness of these disciplines, including the interactions and relationships of basic system and cost factors.

The guidebook covers all aspects of well controlled R&M programs whose detailed application extends from predesign concepts through operational deployment and disposal. Included are guidelines and procedures for the definition, evaluation and acquisition of required R&M in Army aviation systems and components. Both government and contractor activities are covered. The guidebook does not provide detailed instructions relative to any specific program or aviation system. Rather, it provides basic definitions, criteria and approaches that form a basis for structuring R&M programs for specific aviation systems. Guidelines presented in this document can be tailored to meet the needs of each program and used to develop individual life cycle provisions and elements that will assure the desired R&M in the field.

The overall approach of this R&M planning guide is embodied in the following basic considerations:

(1) R&M are quantitative characteristics that are predictable in design, measurable in test, controllable in production and sustainable in the field.

(2) Operational reliability of a system is a function of its design, as well as subsequent life cycle activities, where:

(a) design establishes the "inherent" R&M potential of a system and is defined by its engineering documentation, and

(b) subsequent life cycle activities can only degrade R&M below this inherent design level. For example, the transition of a system from a "paper" design to initial production hardware results in reliability below the inherent level. Consequently, assessment of operational reliability must be approached first via its design characteristics (which establish an upper limit of reliability), and then in conjunction with a series of modification factors that account for production and operation and maintenance (O&M) degradation.

(3) In order to achieve and retain acceptable levels of operational reliability, deliberate and positive R&M engineering action must be taken throughout a system life cycle.

(4) The improvement and growth of operational reliability, to levels which approach the inherent value for a given system, is best accomplished in the early stages of design and development. This improvement and growth is performed through implementation of highly disciplined and systematic engineering and test activities which enhances inherent reliability by forcing the design to be iterated, and which minimizes production and operating and maintenance (O&M) degradation by eliminating potential failures and manufacturing flaws prior to production.

This guidebook also recognizes that many Army aviation systems are currently fielded or are in the later stages of development or production, and that certain Army aviation system developments are modified versions of prior military or commercial aircraft.

Accordingly, the guidebook covers all procurement programs, ranging from initial development to procurement of existing systems, and is applicable to basic military aircraft and military adaptations of commercial aircraft.

1.2 Basic R&M Concepts

In order to establish the theoretical framework for the guidelines and procedures given later, and to provide an engineering preamble to the remainder of the guidebook, a brief summary of basic R&M concepts is given in the sections which follow. Section 1.2.1 discusses hardware reliability and life characteristics; section 1.2.2 discusses reliability degradation factors during production, operation and maintenance; and section 1.2.3 discusses the reliability growth process.

1.2.1 Reliability and Life Characteristics

The term reliability is defined as the probability that a hardware item (i.e., system, equipment, component) will satisfy its performance requirements for a specified time interval under operational conditions. The reliability definition stresses four elements: namely, probability, performance requirements, time and use conditions. Probability is the likelihood that an event will or will not occur. It is a quantitative term expressed as a value between 0 and 1. Performance requirements indicate that criteria must exist which clearly specify, describe or define what is considered to be satisfactory operation. Time represents a measure of a period during which we can expect satisfactory performance. Operational conditions represent the environmental conditions under which we expect the item to function.

Determining reliability involves an understanding of concepts pertaining to failure rate as a function of age. A failure rate is a measurement of the number of malfunctions occurring per unit of time. Separate consideration is given to three discrete periods when viewing the failure characteristics of a complex hardware

item or system over its life span (and when considering a large sample of its population). These periods are shown in Figure 1-1.

The time periods shown in Figure 1-1 are characterized as follows:

(1) Initially, the item population exhibits a high failure rate. This failure rate decreases rapidly during this first period (often called the infant mortality, burn in or debugging period), and stabilizes at an approximate value (at time T_B) when the weak units have died out. It may be caused by a number of things: gross built-in flaws due to faulty workmanship, transportation damage, installation errors or other latent defects. This initial failure rate is unusually pronounced in new equipment. Many manufacturers provide a "burn-in" period for their product prior to delivery which helps to eliminate a high portion of the initial failures, and assists in establishing a high level of operational reliability.

(2) The item population, after having been burned-in, reaches its lowest failure rate level, which is normally characterized by a relatively constant failure rate, accompanied by negligible or very gradual changes due to wear. This second period (between T_B and T_W) is called the useful life period, characterized mainly by the occurrence of chance or random failures. The exponential failure distribution is widely used as a mathematical model to approximate this time period. While this period varies among hardware types and is the interval usually given most weight in design reliability action, it is the most significant period for reliability prediction and assessment activities.

(3) The third and final period occurs when the item population reaches the point where the failure rate starts to increase noticeably (T_W). This point is identified

$$R(t) = \epsilon^{-\int_0^t \lambda dt}$$

General Equation Applies to All Possible
Kinds of Failure Distributions

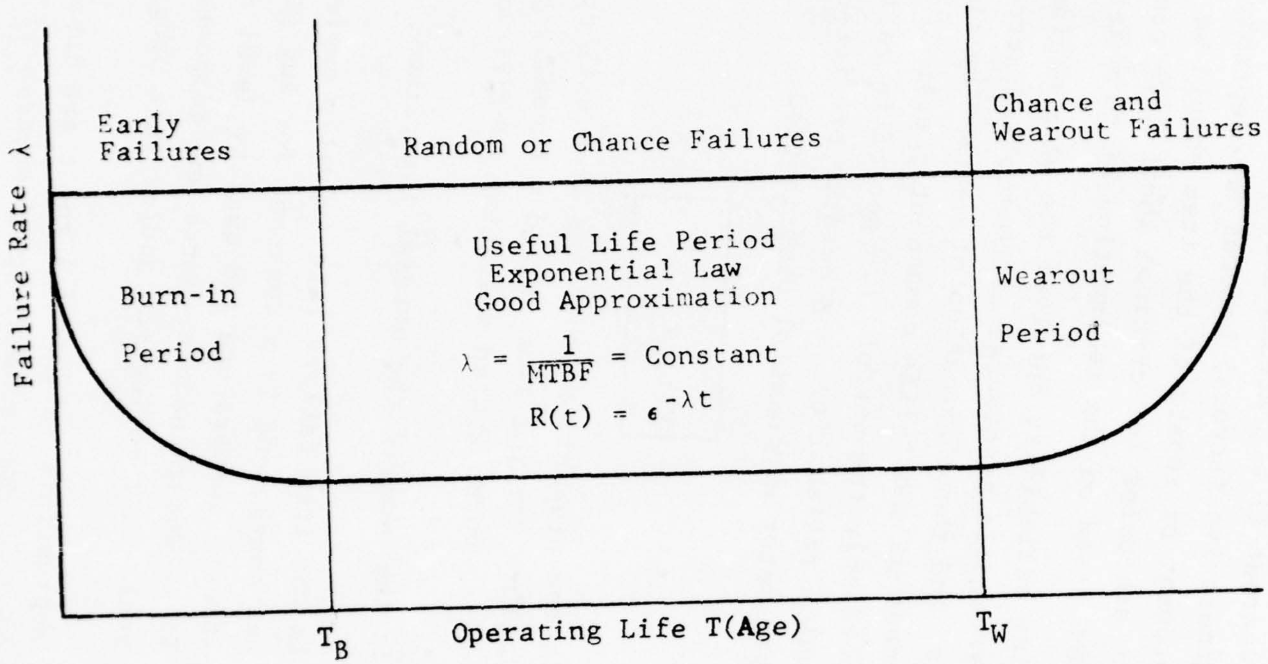


Figure 1-1

LIFE CHARACTERISTIC CURVE

as the end of useful life or the start of wearout. Beyond this point on the time axis, the failure rate increases rapidly. When the hardware failure rate due to wearout (i.e., accumulated damage, fatigue and/or degenerative factors) becomes unacceptably high, replacement or repair of the item should be made. Replacement schedules (of critical short-life components) are often based on the recognition of this failure rate.

Optimizing reliability involves the elimination of early failure by systematic procedures of controlled screening and burn-in tests, and the elimination of wearout by timely preventative replacement of short-life component parts. The general technique considers only the useful life period in reliability design efforts in which reliability is generally predicted by means of the single parameter exponential distribution:

$$\boxed{R(t) = \epsilon^{-\lambda t}}$$

$R(t)$ is the probability that the item will operate without failure for the time period t (usually expressed in hours) under stated operating conditions.

ϵ is the base of the natural logarithms; equal to 2.7182...

λ is the item failure rate (usually expressed in failures per hour), and is a constant for any given set of stress, temperature and quality level conditions. It is determined for parts and components from large scale data collection and/or test programs.

When appropriate values of λ and t are inserted into the above expression, the probability of success (i.e., reliability) is obtained for that time period.

The reciprocal of the failure rate is defined as the mean time between failures (MTBF)

$$\boxed{MTBF = 1/\lambda}$$

The MTBF is primarily a figure of merit by which one hardware item can be compared to another. It is a measure of the failure rate (λ) during the useful life period.

The concepts associated with the three time periods shown in Figure 1-1, when implemented through appropriate techniques described later, can be used to establish (and ultimately control) the reliability potential of the system under consideration. The section which follows (Section 1.2.2) discusses how degradation in reliability can occur during production and operational phases of the life cycle. Section 1.2.3 briefly discusses how reliability can grow from a degraded level back up to that which approaches the inherent value of a system. Reliability growth is described in further detail later in this guide.

1.2.2 Reliability Degradation

It must be emphasized that reliability (or MTBF) estimates which are based solely on the concepts discussed in Section 1.2.1 reflect the reliability potential of a system during its useful life period (i.e., the period after early production where quality defects are dominant, and prior to the time when wearout becomes dominant). Reliability estimates which are based solely on random failures occurring during the useful life period represent only one piece of information covering an aviation system's reliability capability. These estimates do not reflect the expected system performance after initial manufacturing and when operated and maintained in its field environment. Estimates prepared strictly in accordance with the general technique characterized in Section 1.2.1 reflect the inherent reliability of a system which is defined by its engineering documentation, its stress and safety

factors and gross environmental application, manufacturing and quality factors.

Experience factors indicate that the reliability of a system or component item as it leaves production (particularly early production) has been found to be much less than its inherent (random failure) reliability. In order to assess the magnitude of the reliability degradation due to manufacturing, the impact of manufacturing process, i.e., the process induced defects, the efficiency of conventional manufacturing and quality control inspection, and the effectiveness of reliability screening tests must be evaluated. Within this framework, two types of defects are considered: 1) quality defects, and 2) reliability defects. These can be further subdivided into intrinsic and induced defects. The intrinsic defects arise from the basic limitations (i.e., failure rates) of the constituent parts used in the item and are a function of part vendor's process maturity, inspection and final test methods. The intrinsic reliability is synonymous with inherent (or reliability potential defined in Section 1.2.1) reliability and is calculated using standard handbook techniques. Induced defects are those which enter the item as a result of the manufacturing process stresses, handling damage or operator errors.

Note that a part vendor's process maturity is dependent upon how well he can reduce the number of process induced defects which escape detection and are delivered to the customer (i.e., system contractor). A system contractor usually views a parts vendor's product as having reached maturity (especially if it has a favorable production history) and calculates its inherent reliability using the standard handbook techniques.

The role of conventional inspection is to weed out defects based on visual observation and/or measurements. A well planned inspection station utilizing detailed criteria and instructions, proper instrumentation and trained personnel will weed out more

defects and will have a high inspection efficiency. This efficiency can be modeled in terms of a factor whose value (numerically ranging between 0 and 1) depends on the rigor of the inspection operation. Note, however, that no inspection is perfect. A 100% error-free inspection station is impossible to attain.

Similarly, a screen or screening test involves the application of time-stress techniques for converting latent reliability defects into actual defects which can then be removed by conventional inspection methods. Ordinarily, screening tests are derived from ongoing failure mode studies which identify intrinsic and process related failure mechanisms. The ability of a screening test to convert latent defects into actual defects can also be modeled by means of a strength factor. This factor characterizes the ability of the screen to convert latent defects to actual defects based on time, type of stress and stress level.

Degradation in reliability also occurs as a result of system operation as previously indicated. Wearout, with aging as the dominant failure mechanism, can shorten or reduce the useful life, particularly of mechanical systems such as helicopter systems.

Situations occur in which a military helicopter may be called upon to operate beyond its design capabilities because of an unusual mission requirement, or to avoid a ground threat. These situations could cause ill effects to its structure or dynamic components. Operational abuses due to rough handling, heavy loads or neglected maintenance, can contribute materially to reliability degradation which eventually results in failure. This degradation can be considered a result of the interaction of man, machine and environment. The translation of the factors which influence operational reliability degradation into useful procedures requires a complete statement of functions for man and machine, plus stimulus conditions which could degrade operator performance.

Degradation in inherent reliability can also occur as a result of maintenance activities. Studies have shown that excessive handling brought about by frequent preventative maintenance

or poorly executed corrective maintenance (e.g., installation errors) have degraded system reliability. Recent trends in system design have attempted to reduce the amount of human involvement via Built-In Test Equipment (BITE) and other diagnostic and prognostic factors which ease the maintenance burden. In order to assess the degradation effects of maintenance, one must evaluate both the design and the effects of poorly trained or unskilled technicians.

From the above discussion, it is evident that total reliability for any given system is a combination of the designed-in inherent reliability plus a series of degradation factors which occur during production, operation and maintenance. Later sections of this guide will show how the inherent system reliability can be enhanced and degradation factors minimized.

1.2.3 Reliability Growth During Development

Reliability growth represents a process during the development phase by which a hardware item approaches reliability maturity. As indicated in Section 1.2.2, the reliability of a newly fabricated item, or an off-the-board prototype, is much less than its design reliability potential. This is because of initial design and engineering deficiencies as well as built-in manufacturing flaws.

The basic concepts associated with a reliability growth process and its application to newly fabricated hardware involves consideration of hardware test, failure, correction and retest activities. Specifically, reliability growth is an iterative test-fail-correct process. There are three essential elements involved in achieving reliability growth, namely:

(1) Detection and analysis of hardware failures.

(2) Feedback and redesign of problem areas.

(3) Implementation of corrective action and retest.

The rate at which hardware reliability grows is dependent on how rapidly these three elements can be accomplished and,

most importantly, how well the corrective action effort solves the problem identified. During early development and test activities, the achieved reliability (or MTBF) is well below that predicted on the basis of design analyses and analytical predictions. As development and test efforts progress and further problem areas become resolved, measured reliability values approach the inherent (design based) value. Figure 1-2 depicts this process.

As production begins, a decrease in reliability is characteristic, due primarily to workmanship errors resulting from unfamiliar operations. As production continues, and skill increases, the measured reliability again approaches the inherent value.

The specific application of growth concepts to formal reliability growth testing represents a management technique useful for meeting system program objectives in planning and resource allocation. As such, the principal benefit is a quantitative methodology for accurately determining the time and costs required to grow to a given level of reliability under varying degrees of corrective action rigor.

1.3 Guidebook Organization

Figure 1-3 identifies applicable chapters in the guidebook which correspond to major reliability and maintainability activities. These activities are performed by government and/or contractor during development, production, and deployment of reliable aviation systems and components. These activities are listed in the approximate chronological order of their application during the system life cycle.

1.4 Life Cycle Reliability and Maintainability

The life cycle applicable to Army aviation systems is subdivided into distinct phases, as indicated in AR-702-3, and which parallels the life cycle activities described in DA Pamphlet 11-25, Life Cycle Management Models for Army Systems (LCMM).

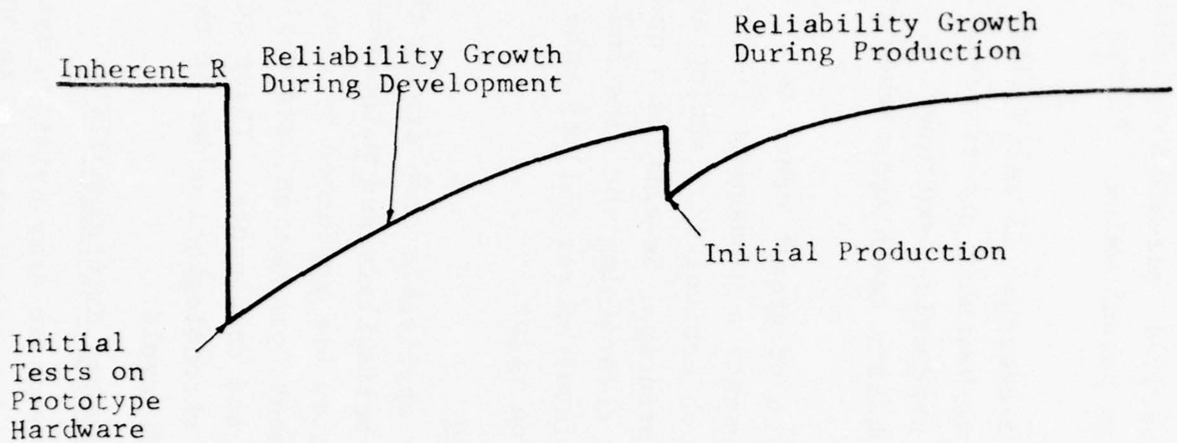


Figure 1-2

RELIABILITY GROWTH PROCESS

TO PERFORM THESE FUNCTIONS	USE THESE SECTIONS OF THE GUIDEBOOK																	
	3.2	3.3	3.4	4.3.1	4.3.2	4.3.3	4.3.4	4.3.5	4.3.6	5.3	5.4	5.5	5.6	5.7	5.8	App A	App B	App C
Plan R&M Programs	●	●										●	●	●		●	●	
Define Requirements	●	●	●														●	
Prepare Work Statements and R&M Specifications	●	●	●							●								
Estimate Time and Costs										●	●	●	●	●	●			
Evaluate Proposals			●								●							
Prepare an R&M Program Plan	●	●	●															
Monitor an R&M Program			●															
Allocate R&M				●	●	●												
Perform R&M Predictions				●	●	●												●
Perform Failure Mode Analysis							●											●
Conduct M Demonstration								●										
Manage Critical Item Control & Standard Program		●	●															
Conduct Program Reviews		●	●															
Perform Failure Analysis									●									●
Conduct Growth Testing							●											
Perfrom R&M Assessments				●	●	●												
Assure Production R							●											●
Assure R During Field Maintenance & Overhaul		●	●															
Collect Data	●	●	●														●	
Administer R&M Programs	●	●	●							●	●	●	●	●	●		●	

Figure 1-3
GUIDEBOOK ORGANIZATION

Appendix A provides a flow chart that describes these activities and shows specific events which occur during each period of the Army procurement, development and deployment effort.

The major R&M system life cycle considerations are given in Figure 1-4. This figure shows that R&M maturity for aviation systems can only be reached through the application of systematic and controlled R&M analyses and tasks beginning at concept and extending through production, field operation and disposal. Such considerations are an integral part of the aviation system development during which the required levels of effectiveness are planned, achieved and maintained at minimum total cost.

A brief summary of the specific tasks for each of these phases is given below:

(1) Conceptual Phase--involves R&M planning, trade-off studies and identification of areas of high technical risk. R&M activities during this phase are to be correlated with the Army's development test (DT) and operational test (OT) planning activities.

(2) Validation Phase--involves R&M inputs to requests for proposal (RFP), work statements and preliminary specifications for R&M. Evaluation of proposals for R&M is included during the validation phase.

(3) Development Phase--includes all elements of R&M: contractor program elements, government management and monitoring, R&M engineering, assessment and reporting.

(4) Production Phase--involves production test, failure analysis, data collection, evaluation of change proposals, production controls and management.

(5) Deployment Phase--involves R&M data collection and analysis, reliability integrity during maintenance, R&M assurance of spare parts, and control of product improvements.

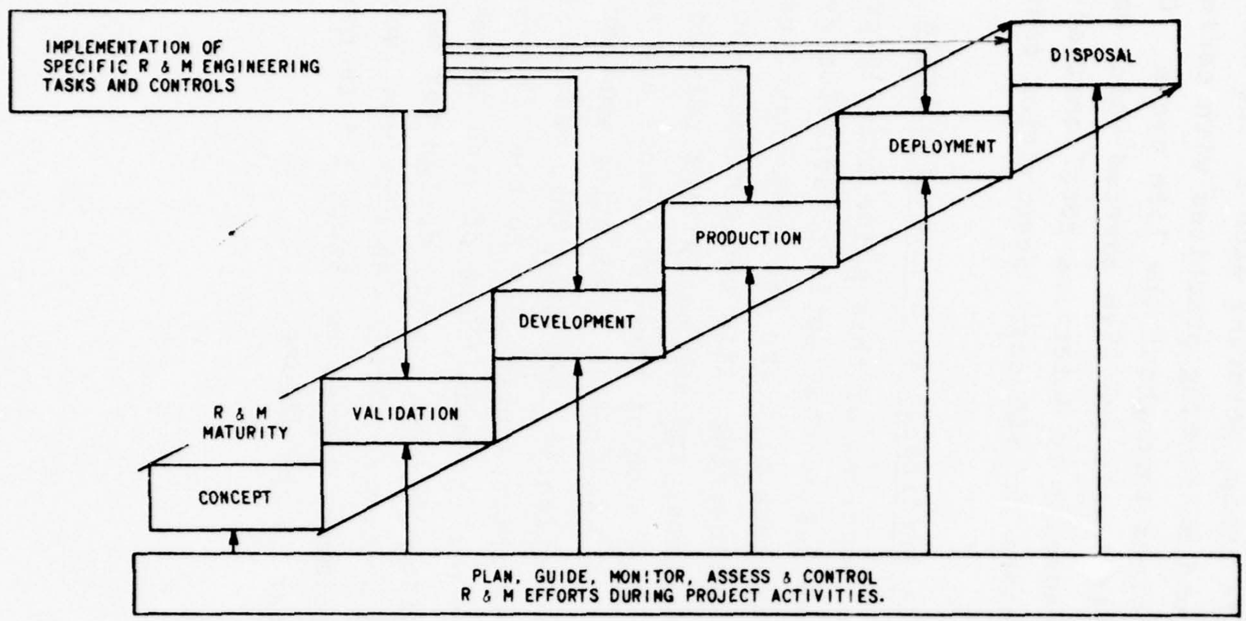


Figure I-4

R & M ACTIVITIES DURING SYSTEM LIFE CYCLE

(6) Disposal Phase--involves the retention of field data and R&M experience once the system is removed from the inventory.

The guidebook is intended to provide detailed guidelines throughout the life cycle, covering each of the above phases, by introducing sound monitoring practices with corrective action criteria at key points throughout the life cycle. Cost factors in terms of the life cycle are also covered which emphasize the performance of tradeoffs to determine total cost-of-ownership, and represent factors for R&D cost, acquisition costs and logistics support cost.

1.5 R&M Documents Applicable to System Life Cycle

The previous sections of this guide briefly provided an overview of activities as they apply to aviation system life cycle phases. Numerous military documents have been prepared covering system engineering, life cycle management, reliability improvement warranties, and R&M activities related to each phase. Figure 1-5 tabulates some of these documents and shows their relationship to the handbook by indicating whether applicability, complexity and practicality are high (H), medium (M) or low (L). It also indicates their application to the life cycle phases as well as to point out the main theme of each document (availabilty, checkout/testing/etc., cost, design for maintainability, ...). Appendix B provides brief descriptions (scope, objective, etc.) of the documents listed in Figure 1-5 in the order in which they appear in the figure.

DOCUMENT NUMBER AND/OR TITLE	RELATION TO HANDBOOK			PHASE IN LIFE CYCLE					EMPHASIS ON:										
	APPLICABILITY	COMPLEXITY	PRACTICALITY	CONCEPTUAL	DEPLOYMENT	DEVELOPMENT	PRODUCTION	VALIDATION	AVAILABILITY	CHECKOUT/TESTING/ETC.	COST	DESIGN FOR MAINTAINABILITY	HUMAN FACTORS	LOGISTICS	MANAGEMENT	MATH MODEL/PREDICTION	MODULARIZATION	SCHEDULING	WARRANTY
AMCP 702-21 Product Assurance Disciplines for the 70's	H	M	M	X	X	X	X	X		X									
AMCP 706-132 Maintenance Engineering Techniques Handbook	M	H	M	X						X		X			X				
AMCP 706-134 Engineering Design Handbook (M Guide for Design)	M	L	L			X						X		X					
AMCP 706-191 Engineering Design Handbook (System Analysis & Cost Effectiveness)	M	H	H					X			X					X			
AR 5-5 The Army Study System	M	H	M	X											X				
AR 11-26 Value Engineering	H	M	M			X	X	X			X				X				
AR 15-14 Systems Acquisition Review Council Procedures	M	L	M	X		X	X	X			X				X				
AR 70-1 Army Research and Development	H	M	M	X		X		X		X					X				
AR 70-10 Test & Evaluation During Development & Acquisition of Material	H	M	M			X	X			X					X				
AR 70-27 Development Plan/Development Concept Paper/Program Memorandum	M	H	M	X						X			X	X	X				
AR 70-37 Configuration Management	L	M	M			X	X					X			X				
AR 70-38 Research, Development, Test & Evaluation of Materiel for Extreme Climatic Conditions	L	H	M			X				X					X				
AR 71-1 Army Combat Developments	L	M	M		X	X				X					X				
AR 71-3 User Field Tests, Experiments & Evaluations	L	M	M		X					X					X				
AR 71-5 Introduction of New of Modified Systems/Equipment	L	M	M		X										X				
AR 95-5 Aircraft Accident Prevention, Investigation and Reporting	L	H	H		X										X				
AR 385-16 System Safety	L	M	H		X	X									X				

Figure 1-5
DOCUMENT MATRIX

DOCUMENT NUMBER AND/OR TITLE	RELATION TO HANDBOOK			PHASE IN LIFE CYCLE					EMPHASIS ON:										
	APPLICABILITY	COMPLEXITY	PRACTICALITY	CONCEPTUAL	DEPLOYMENT	DEVELOPMENT	PRODUCTION	VALIDATION	AVAILABILITY	CHECKOUT/TESTING/ETC.	COST	DESIGN FOR MAINTAINABILITY	HUMAN FACTORS	LOGISTICS	MANAGEMENT	MATH MODEL/PREDICTION	MODULARIZATION	SCHEDULING	WARRANTY
AR 385-40 Accident Reporting and Records	L	M	M		X										X				
AR 700-35 Product Improvement of Materiel	M	M	H		X		X		X					X	X				
AR 700-47 Defense Standardization Program	M	M	H		X	X	X	X						X	X				
AR 700-51 Army Data Management Program	L	M	H		X		X							X	X				
AR 700-90 Army Industrial Preparedness Program (AIPP)	L	M	M				X							X	X				
AR 702-1 Reporting Unsatisfactory Newly Procured and Contractor Maintained Materiel	M	M	H		X						X								
AR 702-3 Army Materiel Reliability, Availability and Maintainability	H	M	H	X	X	X	X	X	X	X				X					
AR 750-1 Maintenance Concepts	H	H	M			X				X					X				
AR 750-37 Sample Data Collection, The Army Maintenance Management System (TAMMS)	M	H	M		X					X					X				
AR 750-43 Test Measurement & Diagnostic Equipment (TMDE)	M	M	M		X	X	X			X					X				
AVSCOM-PAM-702-1 Critical Parts Management	M	M	H		X	X	X					X			X				
DRSAU-TR-76-11 Reliability Prediction, Assessment & Growth	H	M	H				X								X	X			
MIL-HDBK-217A Reliability Stress & Failure Rate Data for Electronic Equipment	M	M	H			X	X								X				
MIL-HDBK-472 Maintainability Prediction	H	M	H			X						X				X			
MIL-Q-9858A Quality Program Requirements	M	M	M			X									X				
MIL-STD-470 Maintainability Program Requirements for Systems and Equipment	M	M	H			X						X							
MIL-STD-471 Maintainability Demonstration	L	M	M			X						X							

Figure 1-5 (Cont'd)

DOCUMENT NUMBER AND/OR TITLE	RELATION TO HANDBOOK			PHASE IN LIFE CYCLE					EMPHASIS ON:										
	APPLICABILITY	COMPLEXITY	PRACTICALITY	CONCEPTUAL	DEPLOYMENT	DEVELOPMENT	PRODUCTION	VALIDATION	AVAILABILITY	CHECKOUT/TESTING/ETC.	COST	DESIGN FOR MAINTAINABILITY	HUMAN FACTORS	LOGISTICS	MANAGEMENT	MATH MODEL/PREDICTION	MODULARIZATION	SCHEDULING	WARRANTY
MIL-STD-721A Definition of Terms for R Engineering	H	M	M	X	X	X	X	X											
MIL-STD-756A Reliability Prediction	M	M	M			X										X			
MIL-STD-781B Reliability Tests: Exponential Distribution	M	H	H			X				X									
MIL-STD-785 Requirements for Reliability Program	H	H	M			X	X			X			X		X	X			
MIL-STD-882 System Safety Program	L	L	M		X					X		X	X		X				
MIL-STD-891A Contractor Parts Control & Standardization Program	M	M	M			X	X								X				
RADC-TR-69-458 Nonelectronic Reliability Notebook	M	M	H			X				X						X			
RADC-TR-75-149 Reliability, Maintainability & Availability Analysis Tradeoff Tool	L	M	M	X								X							
RADC-TR-76-32 Guidelines for Application of Warranties to Air Force Electronic Systems	M	H	M	X							X				X				X
RDH-376 Reliability Design Handbook	M	H	H			X				X	X	X							
TM 38-750 The Army Maintenance Management Systems (TAMMS)	M	H	M		X									X	X				
TM 38-750-1 The Army Maintenance Management Systems (TAMMS) Field Command Procedures	M	M	M		X													X	
Acquisition Applications	M	H	H	X							X							X	
Advantages & Limitations of Advanced Maintainability Concepts	H	H	H	X						X									
Aircraft Avionics (Digital Avionics Study) Vol IV Appenix C Cost Trade Analysis	M	M	M		X						X			X					
Allocation, Assessment & Demonstration of System MTTR	H	M	M	X		X	X	X								X			

Figure 1-5 (Cont'd)

DOCUMENT NUMBER AND/OR TITLE	RELATION TO HANDBOOK			PHASE IN LIFE CYCLE					EMPHASIS ON:										
	APPLICABILITY	COMPLEXITY	PRACTICALITY	CONCEPTUAL	DEPLOYMENT	DEVELOPMENT	PRODUCTION	VALIDATION	AVAILABILITY	CHECKOUT/TESTING/ETC.	COST	DESIGN FOR MAINTAINABILITY	HUMAN FACTORS	LOGISTICS	MANAGEMENT	MATH MODEL/PREDICTION	MODULARIZATION	SCHEDULING	WARRANTY
Application of the Maintenance Free Systems Approach	L	L	L	X								X							
Applications of Helicopter Mockups to Maintainability and Other Related Engineering Disciplines						X					X		X			X			
Art of Maintainability	H	L	H	X								X							
Automated Test & Diagnostic Equipment for Use in the Maintenance and Repair of Mechanical Equipment	H	M	H		X					X	X					X			
A Case Study of Repair/Discard Implications in ILS	L	M	M		X						X			X					
CH-47A Assessment and Comparative Fleet Evaluation: Executive Summary Report	H	L	H		X									X					
A Computer Model for Economic Analysis of Army Aircraft RAM Improvement Proposals	M	H	L	X					X		X								
Cost Analysis -- What Is It, What Should It Be	M	M	L	X							X					X			
Computer Simulation of Life Cycle Cost Elements	L	H	H	X	X	X	X	X			X								
Cost Effective Approach to Integrated Logistic Support	H	H	L		X						X			X					
Cost Effective Tradeoffs Between Maintenance Procedures for Groups Having Sequentially Deployed Systems	H	H	M	X							X			X					
Cost Estimating Relationships for Field & Depot Maintenance Parts Costs of Army Turbine Powered Helicopters: Army Stock Fund Parts; Pema Second Parts	H	M	M		X						X					X			
Description of a Computerized Model for Specifying Maintenance System Configuration	L	M	L	X												X			
Design for Maintainability. An Intricate Simplicity				X								X							

Figure 1-5 (Cont'd)

DOCUMENT NUMBER AND/OR TITLE	RELATION TO HANDBOOK			PHASE IN LIFE CYCLE					EMPHASIS ON:										
	APPLICABILITY	COMPLEXITY	PRACTICALITY	CONCEPTUAL	DEPLOYMENT	DEVELOPMENT	PRODUCTION	VALIDATION	AVAILABILITY	CHECKOUT/TESTING/ETC.	COST	DESIGN FOR MAINTAINABILITY	HUMAN FACTORS	LOGISTICS	MANAGEMENT	MATH MODEL/PREDICTION	MODULARIZATION	SCHEDULING	WARRANTY
Design Maintainability Into Equipment	H	L	H	X								X							
Development of a Reliability & Maintainability Analysis Technique for Helicopter Research & Development	H	H	M	X												X			
Development of Maintainability Technology for Space Vehicles	L	M	M	X		X				X		X							
Development Program for Field-Repairable Expendable Main Rotor Blades. Phase I Preliminary Design	M	M	M	X							X								
Economics of Introducing Automatic Diagnostic Equipment to Direct & General Support Maintenance (ATE/ICEPM-DS/GS)	H	M	H							X	X								
Economics of Introducing Automatic Diagnostic Equipment to Organizational Maintenance (ATE/ICEPM-ORGL)	H	M	H		X					X	X			X					
Engineering Design Handbook M Guide for Design	H	L	H	X									X						
An Evaluation of Maintainability Requirements Presently Being Stated in Government Contracts	H	M	H				X								X	X			
Evaluation of Proposed Criteria to be Used in the Selection of Candidates for Reliability Improvement Warranties	H	M	H								X								X
Exact Analysis of the Method-One Maintainability Demonstration Plan in MIL-STD-471	L	M	M			X										X			
Executive Summary Report on CH-54A Assessment & Comparative Fleet Evaluations	H	L	H		X						X			X					
Executive Summary Report on Quality & Command Program Assessments	H	L	H		X						X			X	X				
A Generalized Approach for Evaluating Logistics Strategies During Advance Procurement Planning	H	H	M	X							X			X					

Figure 1-5 (Cont'd)

DOCUMENT NUMBER AND/OR TITLE	RELATION TO HANDBOOK			PHASE IN LIFE CYCLE					STRONG POINTS										
	APPLICABILITY	COMPLEXITY	PRACTICALITY	CONCEPTUAL	DEPLOYMENT	DEVELOPMENT	PRODUCTION	VALIDATION	AVAILABILITY	CHECKOUT/TESTING/ETC.	COST	DESIGN FOR MAINTAINABILITY	HUMAN FACTORS	LOGISTICS	MANAGEMENT	MATH MODEL/PREDICTION	MODULARIZATION	SCHEDULING	WARRANTY
Generalized Procedure for Evaluation of Maintenance Aids	H	M	M		X						X								
Government Depot Maintenance Warranties	H	M	M								X								X
Guidelines for Application of Warranties to Air Force Electronics Systems	H	L	H	X	X						X								X
Helicopter Transmission Modularization & Maintainability Analysis	H	M	M	X												X	X		
Impact on Engine Maintainability of Gaseous Radioactive Penetrant Inspections	L	H	L		X														
An Investigation Into the Use of Computer Models During Conceptual Phase Logistics Planning	M	H	M	X										X	X	X			
Life Cycle Cost Analysis Guide	H	M	M	X	X			X											
Life Cycle Cost/System Effectiveness Evaluation & Criteria	M	M	M		X						X			X					
Life Cycle Costing Applied in Evaluating Alternative Short Take-Off & Landing (STOL) Aircraft & Tracked Air Cushion Vehicles (TACV) as Model of Transportation	M	M	M		X					X									
A Logistics Life Cycle Support Cost Model	M	M	M		X						X			X		X			
Logistics Support Life Cycle Model	H	H	M		X	X								X		X			
Maintainability Analysis of Major Helicopter Components	H	M	H	X						X									
Maintainability Engineering Design Notebook, Revision II, and Cost of Maintainability (3 volumes)	M	M	M			X					X	X		X	X				
Maintainability, A Total System Variable	H	M	M		X	X								X					
Maintainability Concepts Used in the Design & Operation of Douglas Commercial Jet Aircraft	M	M	M	X	X										X				

Figure 1-5 (Cont'd)

DOCUMENT NUMBER AND/OR TITLE	RELATION TO HANDBOOK			PHASE IN LIFE CYCLE					STRONG POINTS										
	APPLICABILITY	COMPLEXITY	PRACTICALITY	CONCEPTUAL	DEPLOYMENT	DEVELOPMENT	PRODUCTION	VALIDATION	AVAILABILITY	CHECKOUT/TESTING/ETC.	COST	DESIGN FOR MAINTAINABILITY	HUMAN FACTORS	LOGISTICS	MANAGEMENT	MATH MODEL/PREDICTION	MODULARIZATION	SCHEDULING	WARRANTY
Maintainability Demonstration Procedure & Data	L	M	M				X									X			
Maintainability/Reliability Impact on System Support Cost	L	M	L		X						X			X					
Maintainability, The Measure of Availability	M	H	M		X				X	X			X						
Maintenance Replacement Sequence Selection	M	M	L		X													X	
On Condition Maintenance Programs	H	M	M			X	X			X									
Optimization of the Time Between Aircraft Overhauls by Minimizing Maintenance Cost	H	M	H		X						X					X			
Overhaul Policies for Mechanical Equipment	H	H	M		X						X					X			
Overview of U.S. Army Helicopters Structures R & M	H	H	M		X						X								
A Parametric Life Cycle Cost Model for Army Helicopters	H	H	M	X							X			X					
Potential of Project Prime for Providing Historical Cost Data Required in Integrated Logistic Support Planning	M	M	L	X							X			X	X				
Practical Life Cycle Cost/Cost of Ownership Type Procurement via Lone Term/Multi Year "Failure Free Warranty" (FFW) Showing Trial Procurement Results	H	M	H								X								X
Practical Method of Maintainability Allocation	H	M	L	X		X						X							
Predicting Maintenance Time Distribution of Complex System, Monte Carlo Solution	M	H	L					X				X				X			
Premature Performance of Schedule Maintenance	M	M	H		X													X	
Reliability & Maintainability Analysis of a Two-Year Manned Spacecraft Mission	L	H	L		X											X			
Reliability Engineering Handbook	M	M	M	X		X								X	X				

Figure 1-5 (Cont'd)

DOCUMENT NUMBER AND/OR TITLE	RELATION TO HANDBOOK			PHASE IN LIFE CYCLE					STRONG POINTS											
	APPLICABILITY	COMPLEXITY	PRACTICALITY	CONCEPTUAL	DEPLOYMENT	DEVELOPMENT	PRODUCTION	VALIDATION	AVAILABILITY	CHECKOUT/TESTING/ETC.	COST	DESIGN FOR MAINTAINABILITY	HUMAN FACTORS	LOGISTICS	MANAGEMENT	MATH MODEL/PREDICTION	MODULARIZATION	SCHEDULING	WARRANTY
Reliability Guides (vols 1, 2, 4)																			
Reliability of Airborne Electronic Equipment and Its Effect on Logistics Requirements	M	M	L		X						X			X					
Statistical Approach to Maintainability Allocation	M	H	L	X												X			
Statistical Maintainability Demonstration Plan						X										X			
Status of Maintainability Models: A Critical View	M	M	L				X					X	X	X		X			
The Status of Maintainability Models: A Critical Review	M	M	M	X	X											X			
Subsystem Maintainability Demonstration	M	M	M								X	X							
A Summary & Analysis of Selected Life Cycle Costing Techniques and Models	H	M	M	X							X			X		X			
System Improvement Through Maintainability Demonstration	M	H	L	X		X				X					X				
Systems Maintainability Modeling	M	H	L	X												X			
T63-A-5A Engine Maintainability & Reliability	H	M	M		X													X	
Technique for Determining the Number of Spares with a Prechosen Probability Level	M	H	L	X										X					
Tools of Maintenance	H	L	H							X									
Use of Computer for Predictions of MTTR or Equipments Supported by Automatic Test Equipment	H	H	M					X	X							X			
Use of Computerized Support Modeling in Logistics Support Analysis	H	H	M			X					X			X					
Use of Warranties for Defense Avionics Procurement	H	L	M	X	X						X								X

Figure 1-5 (Cont'd)

Section 2.0

HELICOPTER FAILURE MODE REVIEW

Section 2.0

HELICOPTER FAILURE MODE REVIEW

2.1 General

Section 1.0 of this guidebook indicated that systematic and controlled R&M analyses and tasks must be performed continually throughout a system's life cycle. These R&M activities involve both analytical and test disciplines and techniques. Early analytical R&M activities are performed to insure that the design has a high inherent reliability and to provide for early identification of failure modes. Analytical reliability techniques include apportionment, predictions, FMECA, etc. Reliability prediction techniques, particularly stress strength and probabilistic design analysis, allow the design to be evaluated on paper--thereby uncovering design deficiencies that may lead to failures later. Similarly, reliability growth tests are performed during development to force latent defects to become actual failures, thereby allowing their detection and correction. The reliability growth process requires the detection and analysis of failure, the redesign of the problem area and the implementation of the corrective action.

As hardware progresses through production and into the field, degradation of reliability is common, due to workmanship and maintenance errors. In these later phases of the life cycle, R&M provisions stress production testing, assessment and assurance procedures to minimize hardware reliability degradation. Section 3.0 of this guidebook will define these R&M activities in detail, provide guidelines for their implementation and describe how they can be planned, scheduled and applied during the various life cycle phases.

In order to provide a historical perspective of the helicopter reliability problem, this section reviews past failure modes and causes. A failure mode is a physical description of

the manner in which a failure occurs. A failure cause defines why a failure or a series of repetitive failures occur. In this section, reliability is characterized as the mean-time between failures (MTBF). MTBF is the total operating time accumulated by a population of identical equipment items divided by the number of failures occurring in the time of the observation. When failure information is derived from field data, it is more convenient to use the reliability characteristic MTBR, mean-time-between removal. By removal is meant an unscheduled removal, thereby eliminating scheduled overhauls from the statistic. MTBF and MTBR are equivalent if every failure precipitates a removal and no item is removed that has not failed. Generally, it would not be expected that MTBR equals MTBF unless each removed component is subjected to a failure analysis, and good parts are credited accordingly.

2.2 Helicopter Failure Modes

A gross measure of reliability performance is helicopter flight safety and operational cost history. The percent contributions of major helicopter subsystems to flight safety incidents are shown in Figure 2-1. Maintenance cost factors are shown in Figure 2-2. The figure clearly identifies the dynamic components and the powerplant as being primary contributors to both accidents and maintenance costs. The maintenance record of the OH-58 helicopter indicates similar trends. (Ref. 2-2) The power plant, transmission and drive train (dynamic components) require frequent maintenance attention. The airframe requires a high level of maintenance but accounts for fewer flight safety incidents. The electrical, flight control and avionics systems contribute moderately to the maintenance burden.

It should be pointed out that maintenance data usually includes maintenance and operator damage, equipment scavenging and failures due to environmental causes. During the initial

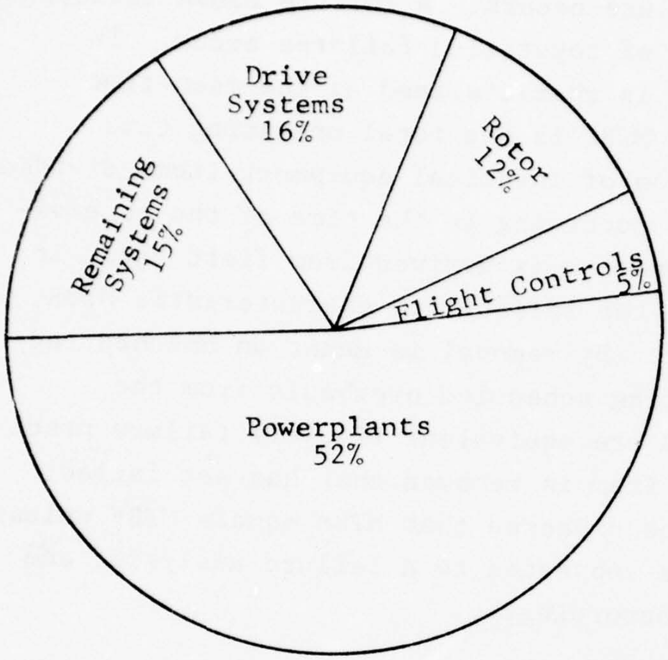


Figure 2-1
COMPONENTS CONTRIBUTING TO FLIGHT SAFETY INCIDENTS

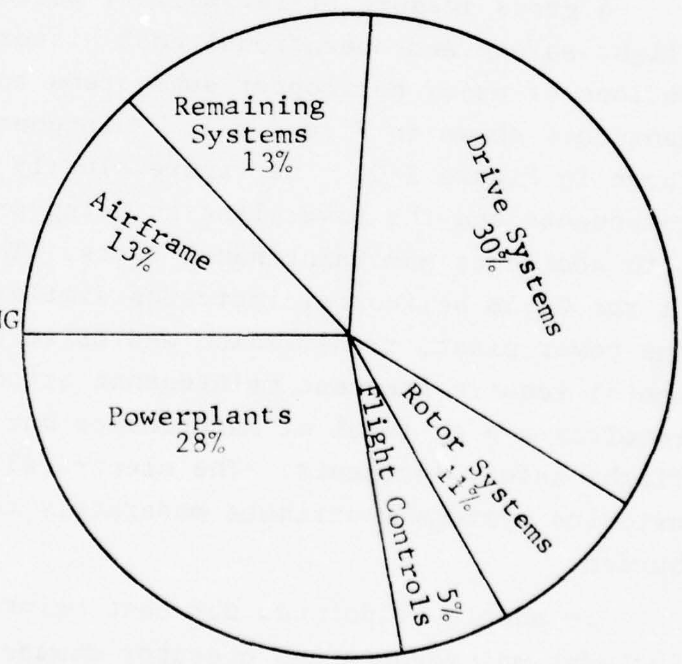


Figure 2-2
COMPONENTS CONTRIBUTING TO DIRECT MAINTENANCE COSTS (Ref. 2-1)

deployment phase, as many as 50% of the maintenance removals of some components have actually been proven to be good units. (Ref. 2-3) The accessibility of components has considerable impact on its removal or repair rate. This has been observed on fuel subsystems, for example, where direct maintenance on the fuel control unit is difficult when the engine is installed in the aircraft.

Gross maintenance information is helpful when identifying R&M problem areas. When detailed hardware failure data are required, further data reduction and analysis is necessary.

2.3 Engine Failure Modes

Past studies of army aircraft R&M characteristics have further defined the component and subsystem contribution to unscheduled engine removal rates. Figure 2-3 summarizes these data and identifies and categorizes both engine caused and non-engine caused failures. Four important R&M indices are listed:

1. Mean time between unscheduled engine removals (MTBR)
2. Mean time between major safety incidents (MTBMSI)
3. Maintenance Manhours (MMH)
4. Time between Overhaul (TBO) (percent contribution)

Engine caused failures are more commonly classed as reliability failures and are clearly so within the jurisdiction of the reliability discipline. Design improvements could also effect the non-engine caused failures, since maintenance errors could be eliminated if the equipment was more reliable and did not require maintenance. Engine caused removals accounted for 27 percent of all removals. Engine caused flight safety incidents accounted for 44 percent of all major safety incidents and 64 percent of maintenance manpower requirements. (Ref. 2-1)

The failure data represent a cross section of Army aircraft engines and engine manufacturers. The engines are:

	Subsystem	MTBR* (HRS)	MTBSI ($x10^5$ HRS)	MMH ($x10^{-3}$)	TBO
Engine Caused	Bearings	9500	2.5	3.5	12%
	Seals	5000	25.0	4.7	
	Compressor	14000	2.1	4.0	63%
	Combustion	25000		19.6	
	Turbine	17000	4.3	19.6	25%
	Cases	185000	100.0	1.5	
	Lubrication	30000	20.0	2.1	
	Fuel	12000	2.1	9.8	
	Air	100000		.2	
	Accessories	40000	14.0	2.3	
	Torquemeters	21000	50.0	.7	
	Electrical	70000	100.0	3.9	
	Exhaust	250000		.7	
	Power Train	77000	33.0	.4	
	Subtotal	(1406 hrs)	(55,045 hrs)	(.073 mmh/flt hr)	
Nonengine Caused	Environment	1700	2.1	1.9	
	Human Error	2300	3.7	9.2	
	Airframe Related	6700	33.0	2.4	
	Scavenging	2000		9.5	
	Unknown	2800	.70	8.5	
	Subtotal	(493)	(45,345 hrs)	(.032)	
	Total	(365 hrs)	(24,863 hrs)	(.105 mmh/flt hr)	

* MTBR--Mean Time Between Unscheduled Engine Romoval

MTBSI--Mean Time Between Major Safety Incidents

MMH--Maintenance Man Hour Rate

TBO--Time Between Overhaul

Figure 2-3

R & M CHARACTERISTICS OF A TYPICAL TURBINE (Ref. 2-1)

- Lycoming T53/T55
- General Electric T58
- Allison T63
- General Electric T64
- Pratt & Whitney T73
- United Aircraft T74

The T58, T64 and T74 engines are not operational within the army.

Inspection of Figure 2-3 indicates that bearings and seal failures account for the greatest number of engine removals. Bearing and fuel problems are the leading causes of major helicopter flight safety incidents, while combustion and turbine failures require the largest maintenance manpower requirements.

Further data analyses and classification reveals the basic failure modes associated with bearing and seal failure. The unscheduled engine removal rate for bearings and seals is shown by engine model number and failure mode, in Figure 2-4. The bearing failure mode distribution differs for each engine type, indicating application and design factors contribute significantly to failure. To improve bearing reliability, several failure modes must be considered concurrently. Correction of any single bearing failure mode may only aggravate another potential failure mode. A development that may lead to improved engine bearing reliability requires forging of the ball bearing and also roller bearing races to obtain grain flow lines parallel to the circumference of the ball. (Ref. 2-4) This development is expected to eliminate several of the failure modes associated with bearing failures. Carbon seal leakage is by far the major seal failure mode. Although this failure mode is easily identified, it does not imply easy solution. For example, an engine weight and volume increase can be expected if a more reliable (e.g., labyrinth type) seal is designed for the engine.

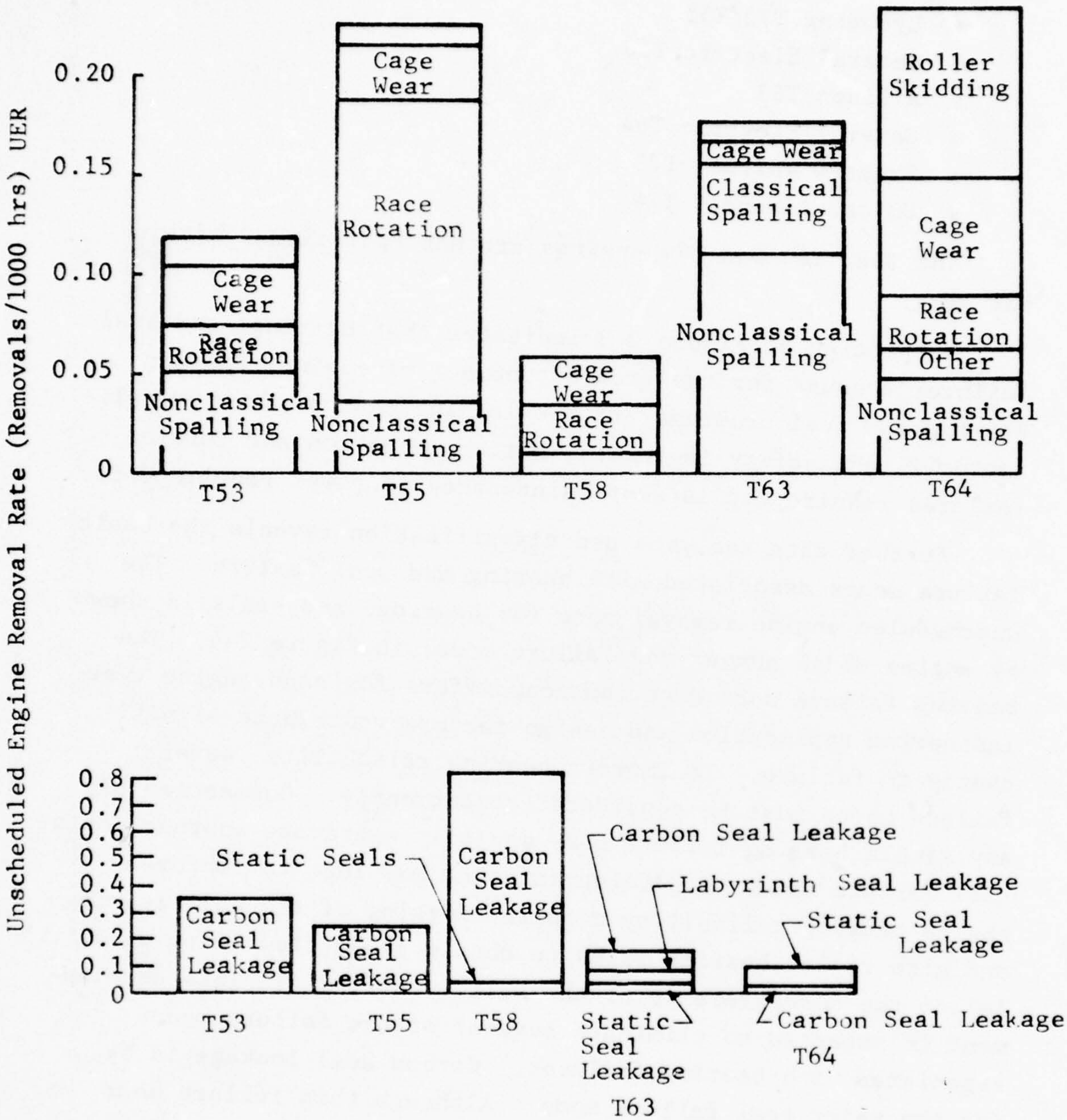


Figure 2-4

BEARING AND SEAL UER RATES FOR VARIOUS ENGINES (Ref. 2-1)

2.4 Transmission Failure Modes

Typical components and parts that make up a transmission assembly include:

- Bearings
- Gears
- Splines and Clutches
- Housings
- Seals
- Spacers, Bearing Liners & Retention Hardware

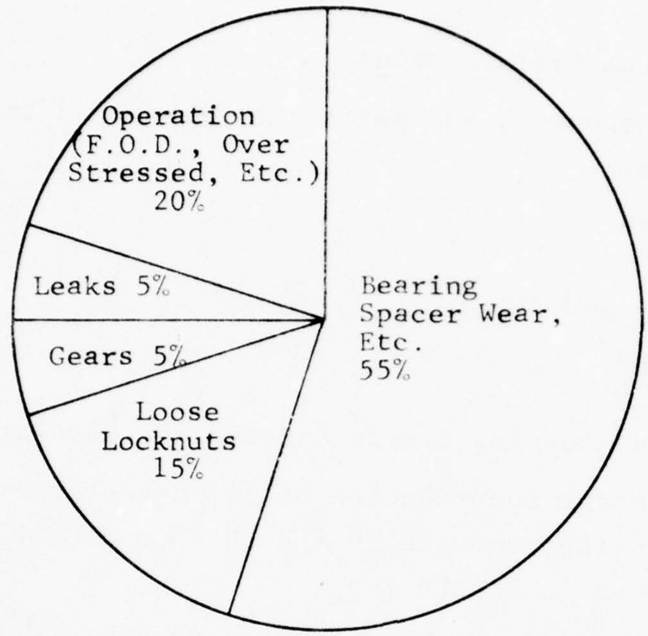
The percentage contribution of failure of these parts that caused transmission removals in the CH-47 and CH-53 series helicopters are shown in Figure 2-5.

Bearings--Bearing failures again contribute significantly to transmission unreliability. The types of bearing failure modes are identical to failures in engines.

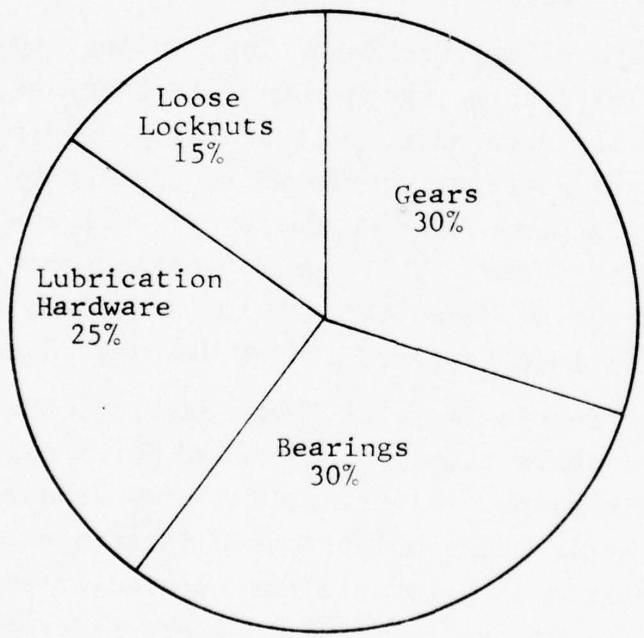
Gear Teeth--Surface fatigure (spalling) of gear tooth profiles relates to the corresponding phenomena in bearings, although the probability of its occurence is less. As a debris releasing failure, spalling degradation can be recognized by debris detection systems. The army spectrometric oil analysis program (ASOAP) is one of these. While seldom catastropic, gear spalling is recognized as potentially being a nucleus for a more serious tooth fatiuge failure, if not discovered and corrected.

Gear Mountings--Particularly in bevel gearing, the attachment of the gear to the shaft through splines or bolts may be prone to fretting deterioration. Fretting is a time dependent phenomena. It exists at nearly every unlubricated interface to a degree; whether that degree is tolerable for particular interface depends upon the severity of the fretting. Severe fretting areas may have catastrophic consequences.

Housings--Cracks have occured in magnesium cases. Occasionally they are the result of random flaws in material and processing, but more often they occur in unflawed castings as the result of vibratory stresses introduced externally.



CH-47 Cause for Transmission Removals



CH-53 Cause for Transmission Removals

Figure 2-5

COMPONENT FAILURES CAUSING TRANSMISSION REMOVALS (Ref. 2-5)

Seals--Seals exhibit a wearout failure mode that results in leakage, and are additionally sensitive to handling and external environment.

Spacers, Bearing Liners, and Retention Hardware--Spacers, liners and other components required to locate bearings have proven to have high failure rate wear problems. Bearing locknuts and other retention hardware have occasionally backed off, sometimes with catastrophic results. The occurrence is random and is usually detectable by debris indicators. A high proportion of locknut failures involve maintenance error, hence failures may be related to the maintenance interval.

During the CH47 development test program and subsequent field tests, over 150 failure modes were identified for the aft, forward, combining and engine transmissions. The MTBF are grouped into four categories and are listed by basic failure mode in Figure 2-6. Fifty percent of the failures had a low MTBF (MTBF < 1000 hrs), and most were discovered during closed loop bench tests of the transmissions. Thirty-nine (39) percent of all failures were identified during bench endurance testing, 34 percent identified during flight testing and an additional 2 percent were uncovered in environmental testing at Yuma, Eglin, and Alaska. It was estimated (Ref. 2-6) that all failure modes could have been identified if artificial constraints were removed and additional reliability testing was performed during the development program. The artificial constraints included lack of load application during endurance testing, inadequate test time, and not using production hardware during early testing. It is not possible to estimate the number of failures that could have been predicted (and corrected) using analytical or probabilistic design techniques. Many of the failure rates listed in Figure 2-6 could have been predicted by using probabilistic fatigue theory, interference theory or semi-empirical design formulas. The high cost of testing and modifying hardware make application of reliability prediction techniques attractive

Failure Mode	No.	MTBF HOURS			
		$MTBF < 1,000$	$1,000 \leq MTBF < 10,000$	$10,000 \leq MTBF < 100,000$	$MTBF > 100,000$
Cracked (Shear)	19	5	6	6	2
Fatigue	13	8	1	0	4
Bearings	41	20	6	7	8
Wear (Also Fretting & Scoring)	27	19	4	0	4
Leakage	12	6	3	3	0
Corrosion	3	0	0	2	1
Spalling	10	9	0	0	1
Other	26	9	5	10	2
	—	—	—	—	—
Total	151	76	25	28	22
% of Total		50%	17%	18%	15%

Figure 2-6

CH-47 ENGINE AND TRANSMISSION FAILURE MODES
(Number of Failures Listed) (Ref. 2-6)

during the detailed design phase. A discussion of these techniques is included in Section 4.0.

2.5 Drive Shaft Failure Modes

Failed components for the CH-47 drive shaft system are identified in Figure 2-7. Drive shaft failures, modes, causes and estimated MTBF are listed in Figure 2-8. A majority of the failure modes were detected during tie down and flight testing. (See Figure 2-9). During early bench endurance testing on the CH47, shafting was not tested. Environmental test time is inadequate to uncover any drive system failure modes. It was estimated that all the failure modes could have been detected during flight testing if the test duration was extended. Maintenance errors were listed (in Figure 2-8) as a major cause of failures. The vulnerability of the drive shaft components to maintenance damage is partially responsible for these failures.

Some of the failures could have been detected during earlier endurance testing if the complete drive configuration was tested. Several failure modes could only be uncovered during tiedown and flight testing since the cause of failures involved interaction with the aircraft structure.

Very few failure modes were predictable using probabilistic design theory, although reliability reviews and checklists applied during the design phase could have forewarned the designer of possible reliability problems.

2.6 Rotor Head Failure Modes

The failed components for the CH47 rotor head are identified in Figure 2-10. Rotor head failure modes, causes and estimated MTBF are listed in Figure 2-11. Although 20 percent of the failures were detected during bench endurance tests, about 40 percent of the failures were detected only after the helicopter was fielded (See Figure 2-12). The primary reasons that failures were not detected in bench or flight tests were:

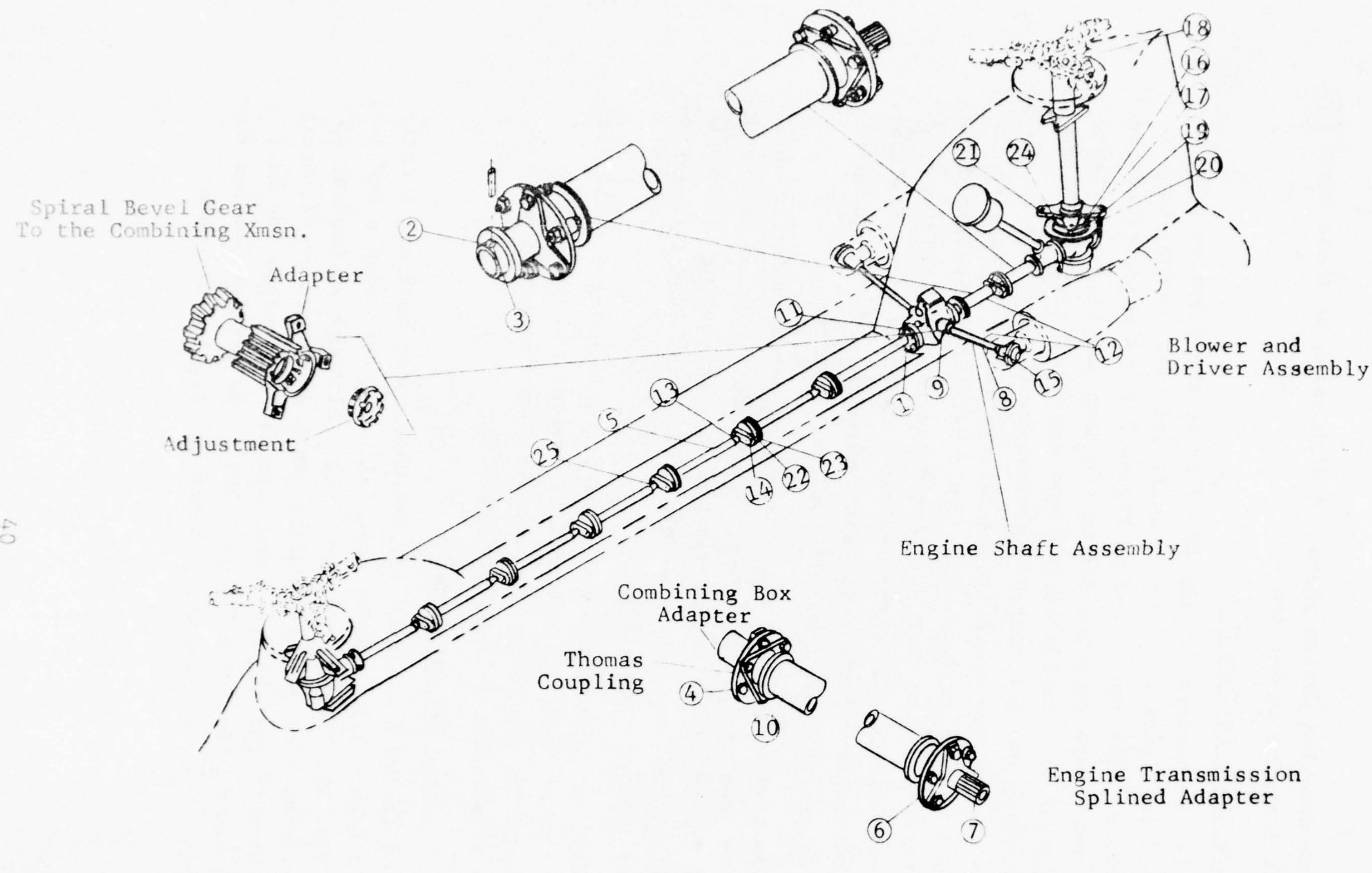


Figure 2 - 7

CH-47 DRIVE SHAFT ARRANGEMENT
(FAILURE MODES LISTED IN Figure 2 - 8)

No.	Failure Mode	Cause	MTBF (hrs)
1	Shaft Adapter Crack	Fatigue	50,000
2	Shaft Adapter Crack	Fatigue in Fretted Hole	1,000
3	Shaft Slot Elongated	Inadequate Clearance	3,000
4	Coupling Gap	Maintenance Damage	1,000
5	Scratches & Gouges	Main. Damage	500
6	Cracked Coupling Plate		5,000
7	Spline Wear		1,000
8	Bearing Failure	Misalignment	1,000
9	Sheared Retainer		5,000
10	Water Entrapment	No Drainage Provisions	10,000
11	Sheared Rivets	Main. Damage	3,000
12	Shaft Vibrations	Poor Spline Lube	1,000
13	Shock Mounts Worn	Dirt & Contamination	500
14	Mount Spring Failure	Excessive Deflection	100
15	Worn Shaft Bushing	Improper Heat Treat	500
16	Thrust Bearing Spall		3,000
17	Gouged Shaft	Main. Error	3,000
18	Nut Thread Damage	Main. Damage	50,000
19	Bearing Oil Line	Main. Error	10,000
20	Bearing Seal Leakage		3,000
21	Improper Installation	Main. Ass'y Error	100,000
22	Mount. Bushing Cracked	Flexing Aircraft	500
23	Mount. Spring Slips	Flexing Aircraft	500
24	Bearing Retainer Crack	Reverse Thrust	1,000
25	Rivets Sheared	Design Deficiency	3,000

Figure 2-8

DRIVE SHAFT FAILURES AND CAUSES (Ref. 2-6)

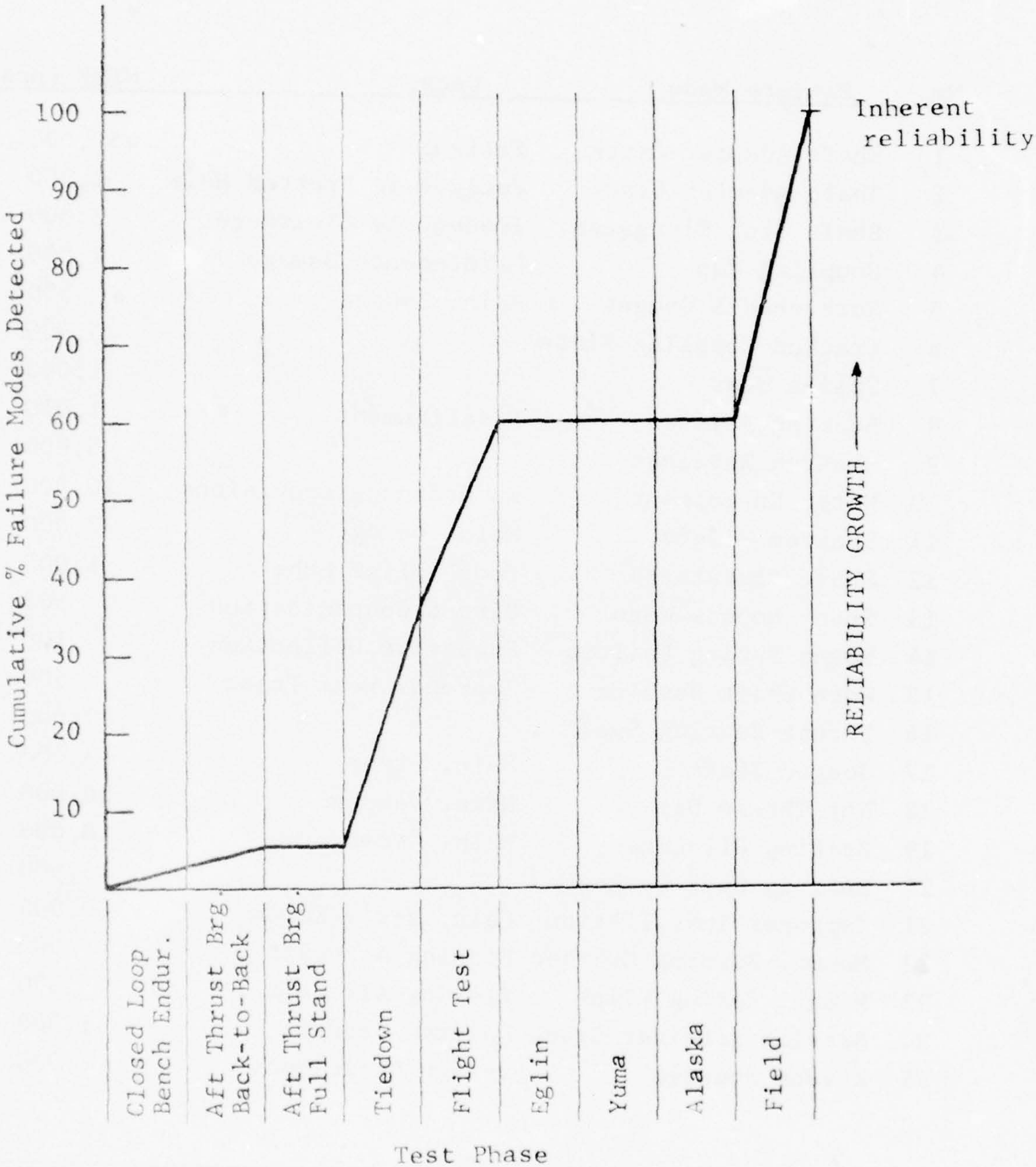


Figure 2-9

FAILURE MODES DETECTED (Ref. 2-6)
DRIVE SHAFTS

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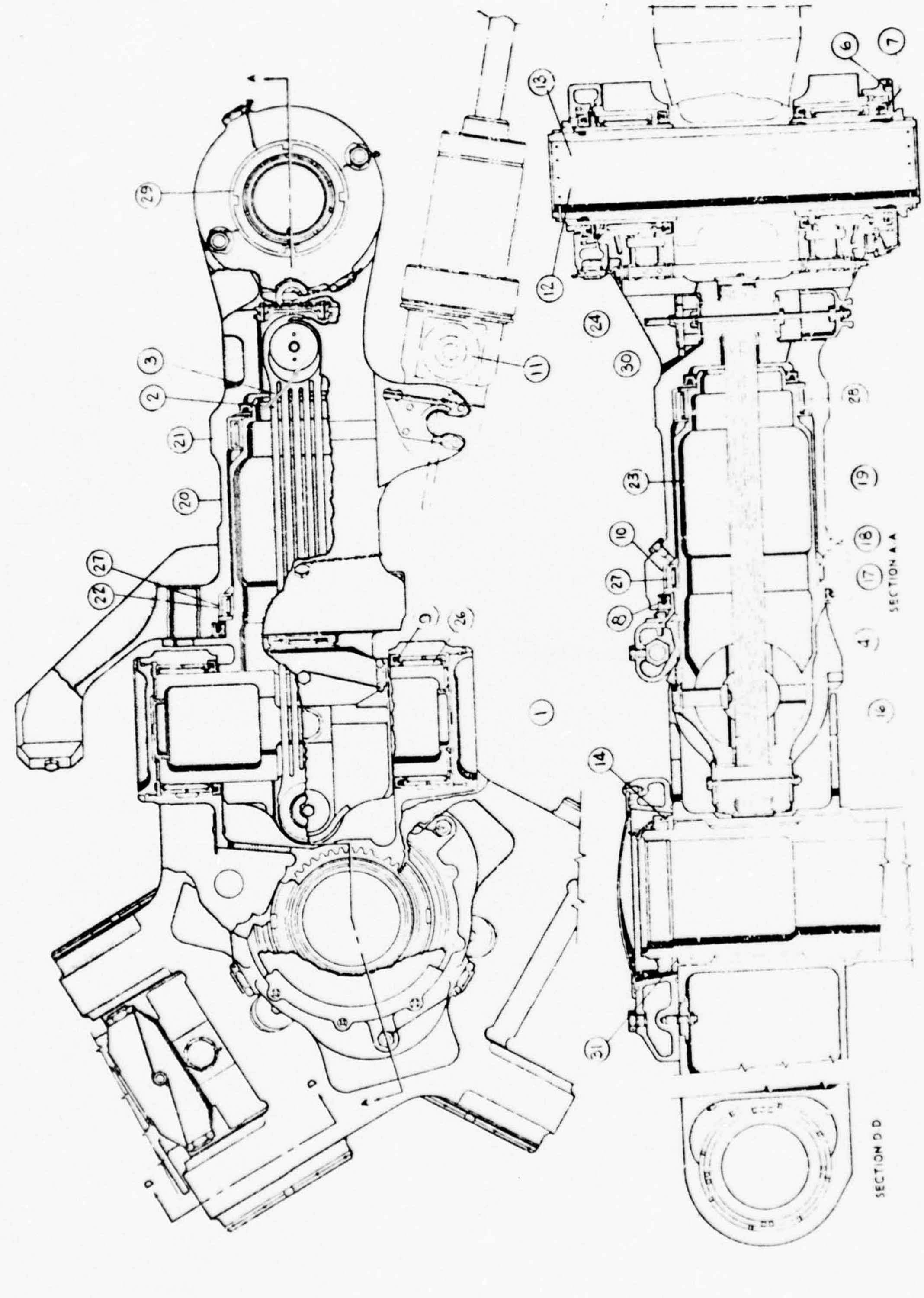


Figure 2-10
ROTOR HEAD

No.	Failure Mode	Cause	MTBF (hrs)
1	Interposer Supports Broken		500
2	Gap Between Tie Bar and Washer	Rotor Overspeed	3,000
3	Tie Bar Pin Fractured	Stress Corrosion	100,000
4	Droop Stops Bent, Distorted & Missing	Blade Flapping	1,000
5	Thrust Washer Galling		500
6	Seal Unseated	Mfg., Out of Tolerance	50,000
7	Seal Leaking		3,000
8	Seal Leaking	Sand Erosion	500
9	Seal Leaking		3,000
10	Bearing Roller, Grinding Undercuts	Mfg. & Quality Control	100
11	Sight Cup Cracked and Broken	Pressure, Temperature & Maintenance	100
12	Vertical Pin Seizing		500
13	Vertical Pin Cracked	Material Defect	100,000
14	Retaining Nut Backing Off		100,000
15	Limited Chafing Grooves in Tanks	Aircraft Vibration	500
16	Droop Stop Wear	Aircraft Vibration	500
17	Spring Leaf Bent and Broken		1,000
18	Tank Assembly Corrosion	Dissimilar Metals	10,000
19	Droop Stop Clevis Broken	Overtorque of Bolts	100
20	Pitch Housing Cracked	Stress Corrosion	100,000
21	Housing Cracked	Stress Corrosion	100,000
22	Pitch Bearing Race Displaced	Maintenance Procedures	100
23	Pitch Shaft Cracked	Operational Error	3,000
24	Bearing Spalling		5,000
25	Bearing, Brinelling and Spalling		5,000
26	Bearing Spalling		3,000
27	Bearing Corroded		3,000
28	Bearing Cage Damaged		5,000
29	Rotor Nut Not Reusable	Nylon Insert Wear	100
30	Flange Bearing Scuffed	Pitch Link Rotation	5,000
31	Spacer Deleted at Installation	Maintenance	100

Figure 2-11

ROTOR HEAD FAILURES AND CAUSES (Ref. 2-6)

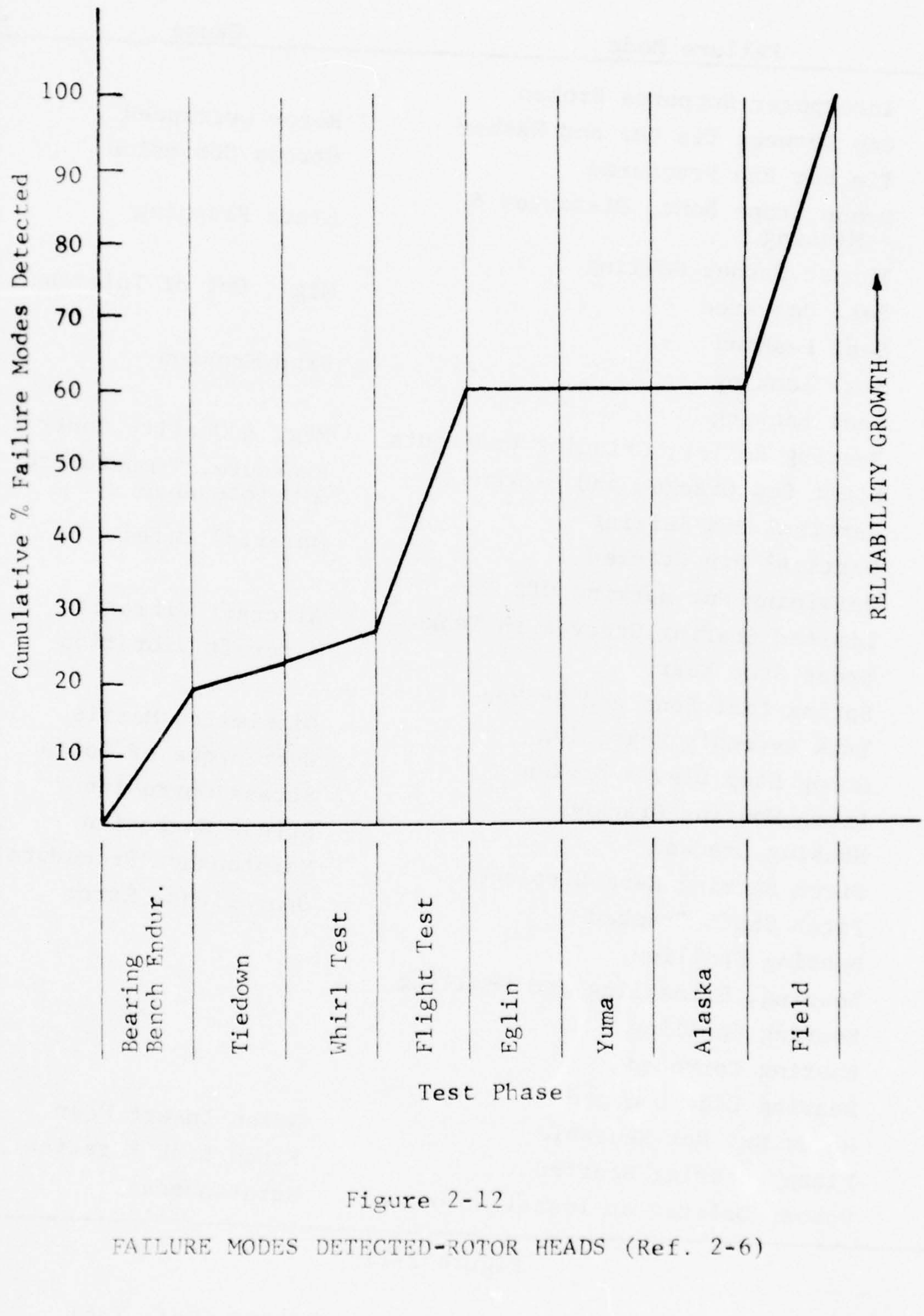


Figure 2-12

FAILURE MODES DETECTED-ROTOR HEADS (Ref. 2-6)

- Inadequate test time
- Dissimilar final configurations
- Varying maintenance procedure between test and field
- No aircraft vibration during bench tests

A majority of failures fell into the categories of:

- Bearing Failure
- Seal Leakage
- Fatigue Failures

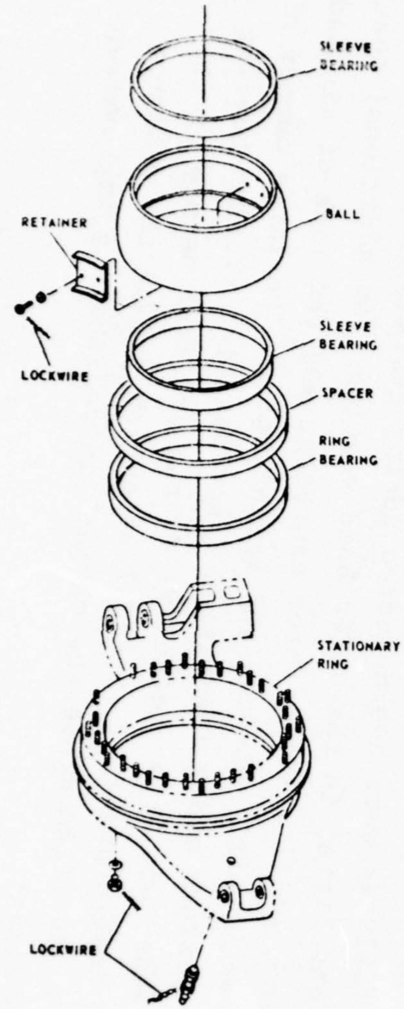
Bearing analysis and fatigue failure prediction techniques may have uncovered many of the potential failures during the detailed design phase.

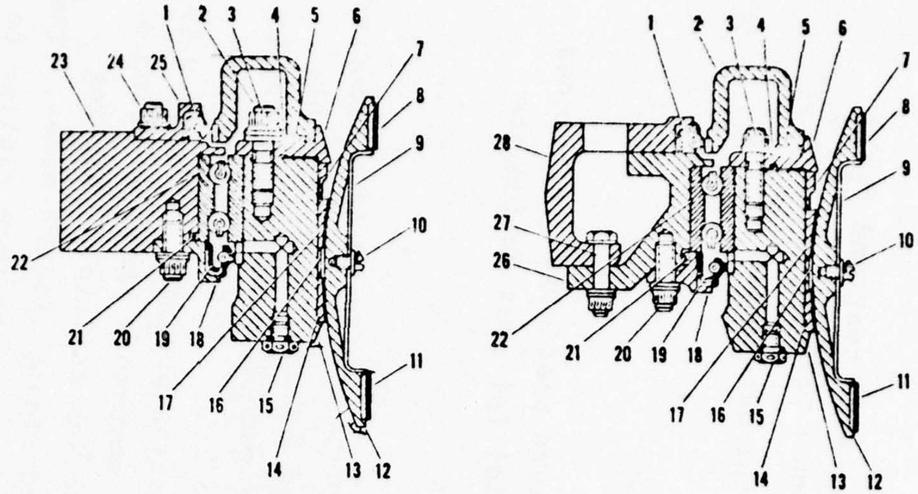
2.7 Rotor Control Failure Modes

Upon examination of the failure data of the CH-47 helicopter series, 23 failure modes were detected for the rotor controls. The swashplate assembly is shown in Figure 2-13 while the failure modes and causes are listed in Figure 2-14. A fairly high percentage (68%) was detected during testing programs. Figure 2-15 shows whirl and swashplate bench and endurance tests as being a moderately successful method of detecting failures. Bearing failures and oil leakage are the predominant failure modes. The reasons failures were not detected during tests were similar to the reasons listed in the rotor head section. An additional test constraint, while testing rotor controls, was the lack of airloads during bench whirl, tiedown and Eglin tests. The large number of bearing failure modes identified (race rotation, Teflon bearing sleeve wear, etc.) is indicative of the critical nature of the bearing design problem. Special attention during the design phase is justified since the payback in reliability improvement is significant.

2.8 Rotor Blade Failure Modes

Rotor blade failures differ from previous dynamic component failure modes due to the blade construction and the aerodynamic loads to which the blade is subjected. Delamination failures are common due to extensive adhesive bonding used in the blade's





1 UPPER OIL SEAL
2 OIL TANK
3 UPPER RETAINER NUT
4 PREFORMED PACKING
5 OIL TANK GASKET
6 UPPER RETAINER
7 RETAINING SPACER
8 UPPER SLIDING SLEEVE BEARING
9 SLIDING SLEEVE BEARING RETAINER
10 SCREW
11 LOWER SLIDING SLEEVE BEARING
12 BALL SPHERICAL BEARING RING
13 STATIONARY INNER RING ASSEMBLY
14 LOWER SPHERICAL BEARING (MATCHED SET)
15 OIL DRAIN PLUG
16 SPHERICAL BEARING SPACER
17 UPPER SPHERICAL BEARING (MATCHED SET)
18 LOWER OIL SEAL RETAINER
19 LOWER OIL SEAL
20 LOWER SEAL RETAINER NUT AND WASHER
21 PREFORMED PACKING
22 SWASHPLATE BEARING
23 OUTER RING (ONE-PIECE MACHINED TYPE)
24 UPPER SEAL RETAINER NUT AND WASHER
25 UPPER OIL SEAL RETAINER
26 LOWER OUTER RING (TWO-PIECE FORGED TYPE)
27 BOLT, NUT, AND WASHER
28 UPPER OUTER RING (TWO-PIECE FORGED TYPE)

Figure 2-13

ROTOR CONTROLS (SWASHPLATE)

No.	Failure Mode	Cause	MTBF (hrs)
1	Swashplate Oil Leak		100
2	Swashplate Ball Dislodging	Inadequate Bonding	500
3	Ball Race Rotating	Inadequate Bolt Preload	500
4	Wear of Teflon Bearings	Rough Surfaces	1,000
5	Flaking of Ball and Slider	Quality Control	500
6	Wear of Ball and Slider	Dirt Contamination	1,000
7	Bearing Spalling		1,000
8	Interference of Actuators	Lockout Blocks Not Used	1,000
9	Retainer Displacement	Lockout Blocks Not Used	10,000
10	Bolt Failure	Material Defect	100,000
11	Clevis Scoring	Rotation of Pitch Links	500
12	Cracked Bushing	Material Defect	3,000
13	Drive Collar Cracks	Excessive Air Loads	5,000
14	Rainshield Cracks	Manufacturing Error	500
15	Rainshield Deflects	High Forward Speed	100
16	Bearing Wear		100
17	Boot Material Deterioration		1,000
18	Sight Gage Glass Loose	Insufficient Edge Crimping	5,000
19	Oil Seal Separates	Different Temperature Expansion	100
20	Lower Ring Cracking	Tool Marks	3,000
21	Cage Scraping Race	Faulty Installation	100
22	Rainshield Cracked	Maintenance Damage	100
23	Rainshield Contacted by Arm.	Rainshield Mfg. Error	100

Figure 2-14

ROTOR CONTROL FAILURES AND CAUSES (Ref.2-6)

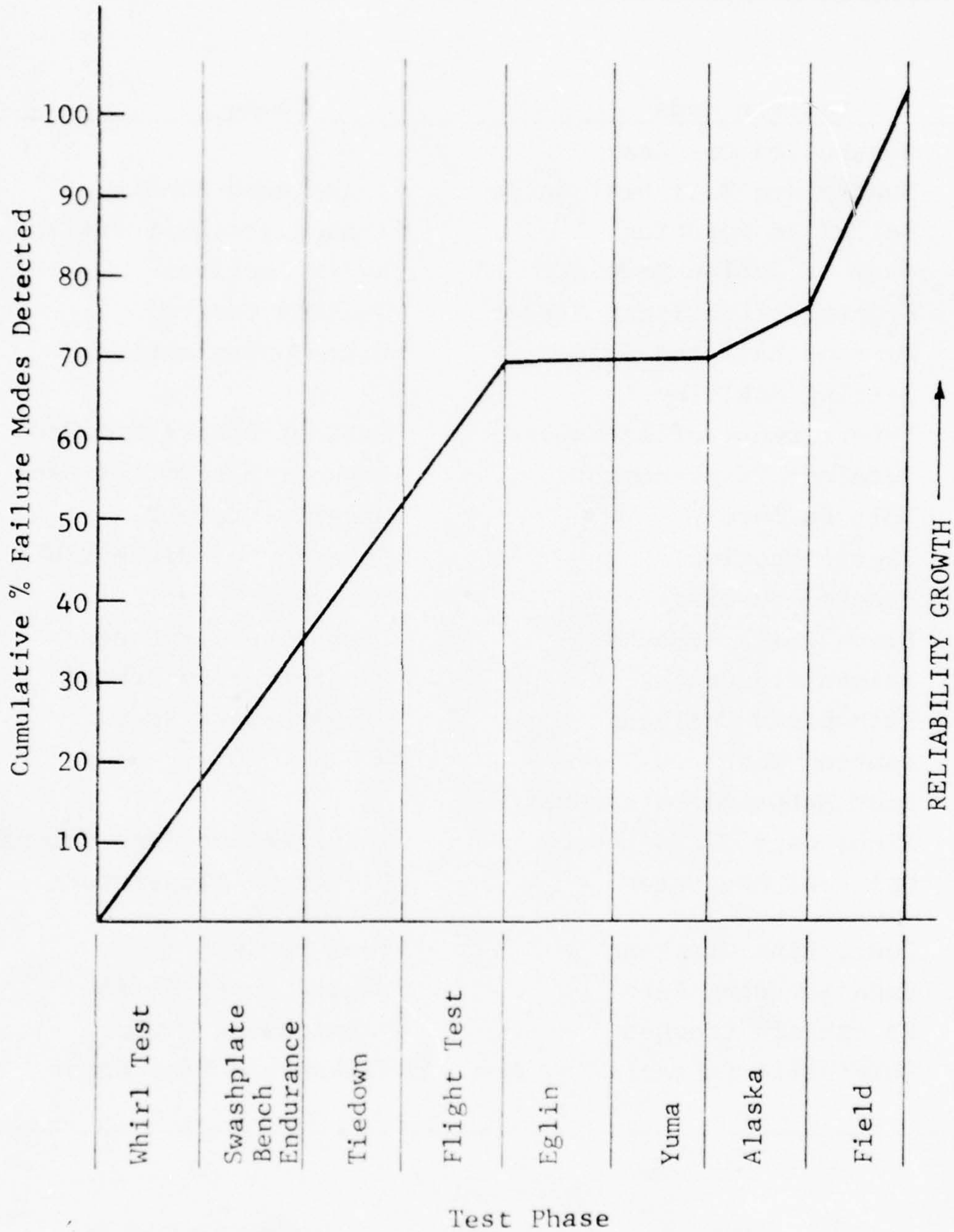


Figure 2-15

FAILURE MODES DETECTED-ROTOR CONTROLS (Ref. 2-6)

construction. Leading edge and tip erosion are also predominant failure modes. The location on the blade where failures occurred is shown in Figure 2-16. Twenty-six failure modes and causes are listed in Figure 2-17. Water entrapment in the blade led to several failures. Quality control of bonded surfaces was identified as a critical problem which seriously degraded reliability. Blade failure caused by environmental factors was effectively detected during testing at Eglin, Yuma and Alaska. The environmental tests (See Figure 2-18) helped achieve a 70% detection record during the testing program. Low cycle fatigue contributed to several failures and may have contributed to delamination and unbonding problems.

In general, the earlier a failure is uncovered, the less costly will be the fix. In some cases the failure modes detected during environmental testing would have been uncovered in early whirl tests if severe environmental conditions could have been simulated.

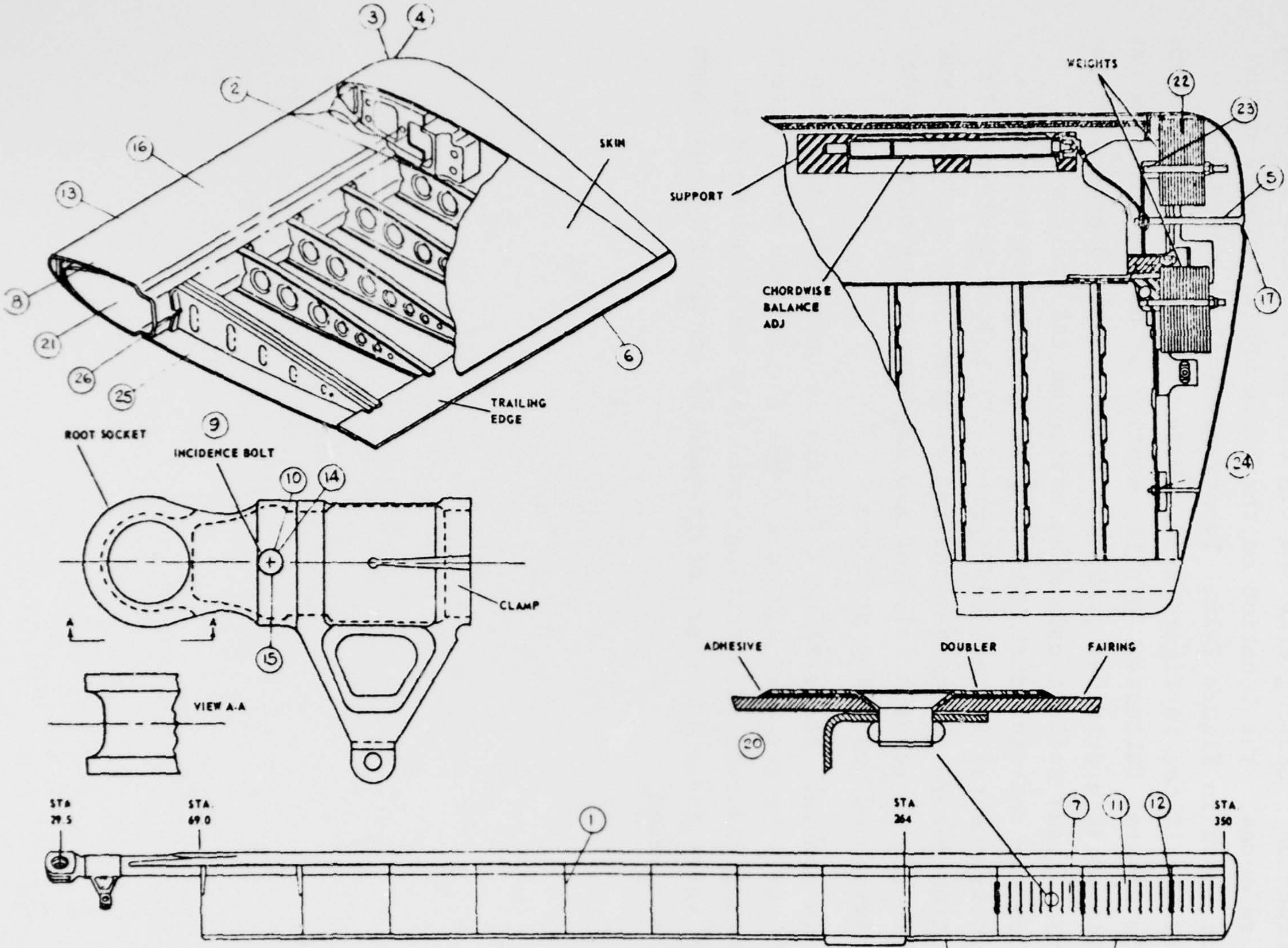


Figure 2-16

ROTOR BLADE (Ref. 2-6)

No.	Failure Mode	Cause	MTBF (hrs)
1	Delamination of Rib Tabs		500
2	Rib Cracking		1,000
3	Tip Cover Cracking	Alternating Air Loads	500
4	Tip Cover Erosion		1,000
5	Tie Fitting Cracked		30,000
6	Trailing Edge Cracking	Nicks on Forward Edge	30,000
7	Spar Doubler Unbonding	Temperature and Humidity	30,000
8	Spar Corroded	Inadequate Protective Coating	1,000
9	Water Entrapment		1,000
10	Incident Bolt Hole Cracked	Burr in Hole	100,000
11	Skin Erosion		
12	Delamination of Doubler	Air Flow	1,000
13	Spar Crack	Excess Blade Flapping	100,000
14	Incidence Bolt Corrosion	Inadequate Protective Coating	30,000
15	Incidence Bolt Fretting		3,000
16	Leading Edge Erosion		1,000
17	Tip Studs Corroded		5,000
18	Fairing Erosion		1,000
19	Skin Delamination	Skin Ply Orientation in Error	3,000
20	Hysol Filler Flaking		1,000
21	Span Crack	Due to Rolling Process	100,000
22	Tip Weight Fitting Unbonding	Poor Quality Control	500
23	Tip Weight Studs Unbonded	Poor Quality Control	10,000
24	Nut Plates Pulled Out	Poor Quality Control	3,000
25	Water Entrapment	Lack of Drainage Holes	100
26	Rib Tab Unbonding	Manufacturing Procedures	3,000

Figure 2-17

ROTOR BLADE FAILURES AND CAUSES (Ref. 2-6)

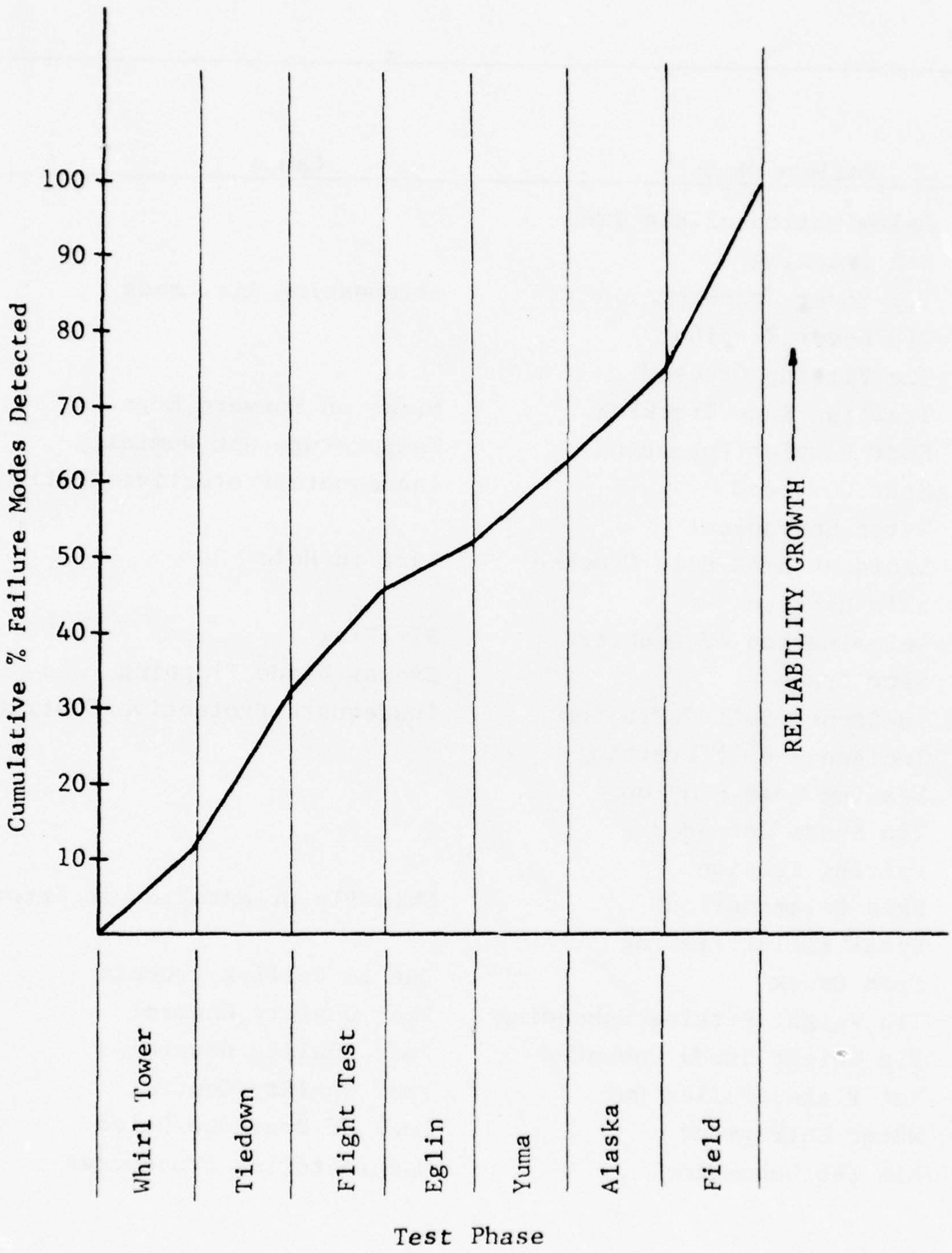


Figure 2-18

FAILURE MODES DETECTED-ROTOR BLADES (Ref. 2-6)

Future helicopter trends and RAM characteristics now seem to be predicted on a number of innovations, among which are included in the following:

- Composite materials--The widespread use of composites in the next generation of helicopters might permit low cost tailoring of shape versus span, greatly increased tolerance to damage, whether from gunfire or impact, and reduce the complexity and hence, the cost of such traditionally high cost components as tail rotor systems and main rotor blades.

- Metallurgical developments--The development and successful adaptation of high-hardness materials to such components as transmission gearing could permit helicopter main transmission assemblies to handle approximately 20% more power at approximately 10% less weight. Such assemblies and other dynamic components, also are being used which will need little or no lubrication and which, in emergency situations, will be able to operate for periods without any lubrication.

- Maintenance warning systems--Such systems are already beginning to appear in present day helicopters and are scheduled for increased use in the next generation of rotary-wing aircraft. These systems are self-checking systems that will warn the operator when they have reached the end of their useful life. This will aid the trend to major subsystems that can be removed or overhauled on an "on-condition" basis, rather than on a specific timetable.

- Increased overhaul periods--The next generation of helicopters could have significantly increased overhaul periods for such dynamic components as rotors, transmissions, controls and drive shafts, with the trend to eliminating specific periods altogether and going to an "on-condition" basis for overhaul.

- Fly-by-wire control systems--Fly-by-wire control systems are also expected in the next generation of helicopters for increased reliability at weight and space savings of up to 50%.
- Noise and vibration reduction--The use of tailored airfoils, made possible by the ease of tailoring composite materials, may even permit drastic reductions in the rotor noise of the next generation of helicopters, possibly the total elimination of the familiar rotor slap. Developments in dynamic insolation might permit reductions of vibration by up to 66% over present day helicopters. This in turn could lead to substantial reductions in total maintenance man hours.
- High-lift airfoils--High-lift rotor air foils have been derived primarily from the supercritical wing technology and subsequently tailored for helicopter use. These show promise of increasing the coeeficient of lift from 10-50% over present helicopters.

Section 3.0

R&M ENGINEERING AND CONTROL PLANNING

Section 3.0

R&M ENGINEERING AND CONTROL PLANNING

3.1 General

As indicated in Section 1.1, AVSCOM's R&M Division is responsible for developing R&M programs, managing and evaluating contractor efforts, providing technical support to on-going projects and performing special R&M tasks. Reliability and maintainability as well as other system characteristics must receive proper consideration during early planning and feasibility study stages and must be rigorously applied with proper emphasis in subsequent life cycle phases. Work efforts begin during conceptual studies and extend through subsequent life cycle phases. This section provides specific guidelines, methods and controls applicable to each phase of the life cycle, with particular emphasis on these activities associated with development and production of aviation systems and components.

The criteria, guidelines and management activities shown here are prepared in consideration of the overall Life Cycle Management Model for Army Systems as shown in DA Pamphlet 11-25 and in conjunction with AR 1000-1 and AR 702-3.

3.2 R&M Life Cycle Activities

The control methods, checkpoints and management techniques utilized by the Army during the procurement of aviation (and other) systems are identified and defined in DA Pamphlet 11-25, entitled "Life Cycle Management Model for Army Systems." A simplified version of this model is given in Appendix A. This model is necessarily general in order to account for the diversity of systems procured. For purposes of this guidebook, a more specific sequence of reliability and maintainability activities is shown in Figure 3-1. Included in this figure are activities which correspond to those shown in Appendix A and which establish points of correlation between both charts.

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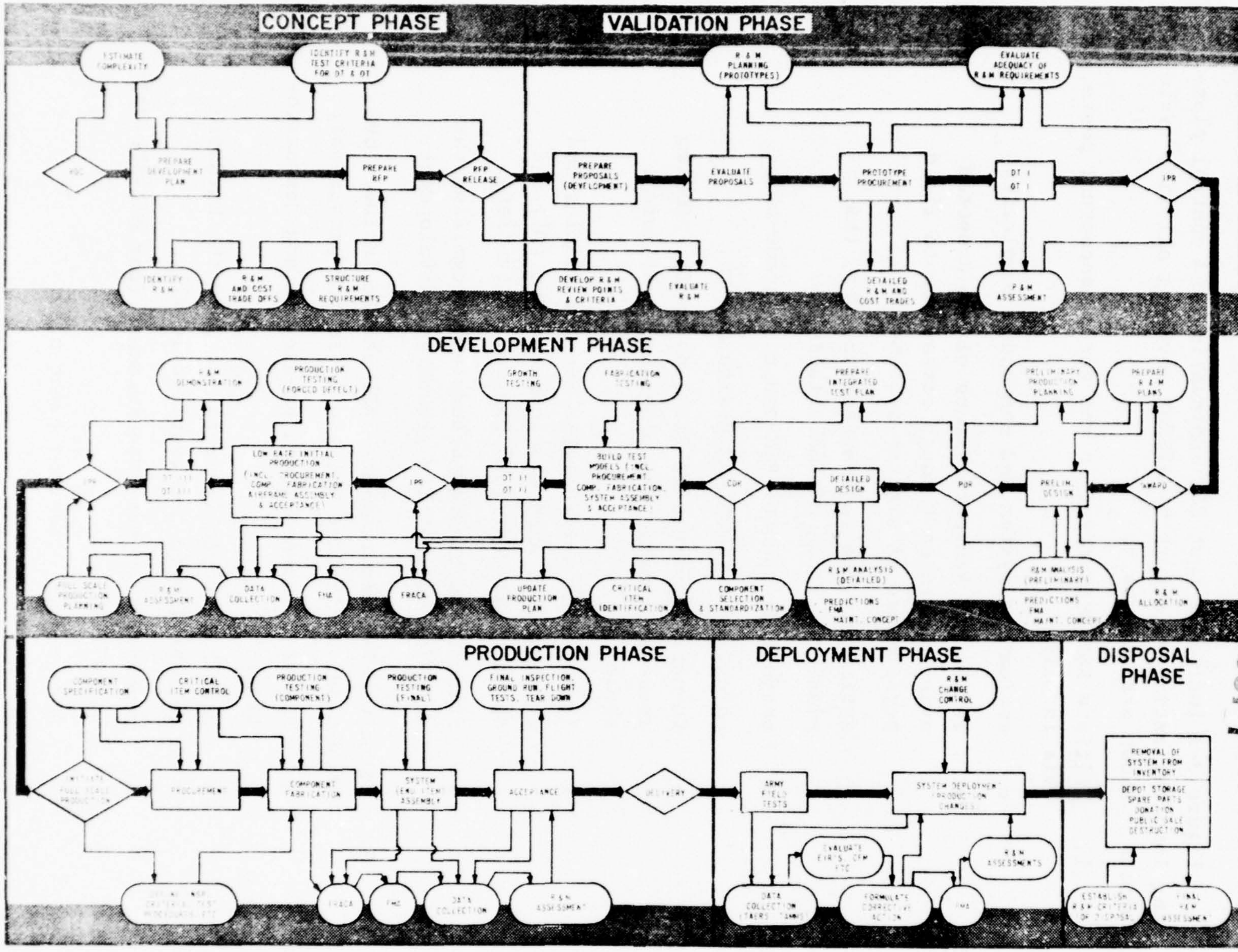

Fig.3-1 LIFE CYCLE R&M ACTIVITIES

Figure 3-1 indicates that R&M engineering and control planning involves extensive effort by AVSCOM covering all life cycle periods. Shown are efforts to:

1. Initiate R&M activities in the early conceptual phase. This involves:

    - estimating system and component complexity,
    - estimating R&M performance of the proposed aviation system through comparison to field performance of similar systems,
    - estimating the cost associated with the predicted range of R&M values,
    - performing special R&M and cost trade-offs,
    - selecting optimum R&M design points,
    - identifying areas of risk, potential problem areas and initiating programs to alleviate these,
    - identifying critical R&M characteristics and criteria for Army development test (DT) and operational test (OT) program activities,
    - structuring program schedules recognizing the need for reliability growth and development.

2. Structure RFP requirements--RFP should include, but should not be limited to, the following provisions:

    - R&M requirements (both prediction and demonstration)
    - growth test requirements (to grow the hardware reliability to the required level),
    - demonstration test requirements (per MIL-STD-781 and 472),
    - R&M program milestone event plan.

3. Evaluate and select equipment contractor(s) during validation--this includes:

   - preparation of a checklist to evaluate prospective contractors intent to comply with R&M requirements--this checklist should cover all R&M program provisions considered applicable, including maintenance concepts and logistic support factors. Section 3.4.2 of this guidebook provides basic criteria that can be used to develop this checklist,
   - planning, management and monitoring of R&M aspects of prototype procurement contracts (if required).

4. Monitor contractor development and production performance. This involves:

   - measuring performance against program requirements and the evaluation checklist,
   - evaluating design growth through monthly submittals of updated assessments,
   - evaluating reliability test (and failure analysis) results,
   - approving effectiveness of corrective action steps.

5. Monitor and evaluate R&M during deployment. This includes:

   - evaluating EIR's, CFM's, TAERS/TAMMS data, PCP's, etc.,
   - monitoring system changes and corrective action implemented in response to observed problems,
   - performing R&M assessments based on observed data.

6. Assess reliability prior to disposal. This includes:

- developing criteria for determining repair economics (i.e., when hardware should be removed from the inventory),
- performing final R&M assessments.

Further examination of Figure 3-1 indicates that a complex set of relationships and interactions exists between functional R&M areas. The interplay of overall management, R&M analysis, component control, system test and other functions is evident throughout the life cycle. Each R&M task can be viewed not only as contributing to the total program, but also as providing timely inputs to other R&M tasks in relation to hardware and planning milestones. For example:

Overall management--begins with the development of criteria for evaluating contractor proposals and extends through preparation of detailed R&M plans during development and production, interacts with detailed R&M work efforts and extends through control of system changes and development of criteria for disposal.

R&M analysis--performed as part of conceptual studies (trade-offs) to establish the optimum level of inherent reliability to be achieved in design. These analyses extend through validation assessments to further define reliability, through analytical studies performed during development to establish the basis for meaningful tests, through production assessments and finally through assessments performed during deployment and prior to disposal to determine achieved levels of R&M.

Component control--includes effort to select, specify and control components, identify critical items and monitor component qualification throughout development

and production of the system, the manufacture of spares and the implementation of component/system changes.

Test program--includes reliability growth testing during development to force out design and fabrication flaws, R&M demonstration prior to production to assure with confidence that the required values are achieved, and forced defect production testing to eliminate process induced quality and reliability defects.

Although Figure 3-1 is a further simplification of Appendix A for R&M activities, nevertheless, it represents a complex set of tasks and controls which may be intimidating at first glance. In order to simplify these interrelated activities in a form that is most useful to the reader, Figure 3-2 has been prepared. Figure 3-2 identifies, in matrix form, those activities normally associated with AVSCOM monitoring/planning tasks and also shows contractor related activities.

Figures 3-1 and 3-2 also indicate that the major thrust of this guidebook is directed toward both AVSCOM and contractor activities which take place primarily during development and production. The following sections further describe these activities. Contractor activities, including procurement options, are defined in Section 3.3 while Section 3.4 of this guidebook provides detailed criteria and guidelines of government (AVSCOM) activities during the various life cycle phases. Included in these guidelines are program planning provisions, evaluation guidelines and monitoring review points.

3.3 Contractor R&M Program

The objectives of a system contractor's R&M program during development and production, in general, are to:

R&M ACTIVITY	APPLICABLE LIFE CYCLE					
	Concept	Validation	Development	Production	Deployment	Disposal
AVSCOM PLANNING AND MONITORING ACTIVITIES						
R&M Planning	•	•	•			
R&M Trade-offs	•	•				
Work Statement Preparation (RFP)	•	•				
Proposal Evaluation		•				
Project Management & Monitoring		•	•	•		
Design Reviews			•			
Test Planning	•	•	•	•		
Logistic Support Analysis	•		•			
Data Collection (field)					•	•
Component Reliability Control			•	•	•	
Evaluation of PIP's			•	•	•	
R&M Assessment			•	•	•	•
Evaluation of Effects of Repetitive Maintenance					•	•
CONTRACTOR ACTIVITIES						
R&M Planning			•			
Design Analysis			•			
R&M Analysis			•	•		
Component Engineering			•	•		
R&M Testing and Demonstration			•	•		
Failure Analysis			•	•		
Production R Assurance			•	•		
Data Collection (factory)			•	•		
Failure Mode Analysis			•	•		

Figure 3-2

R&M LIFE CYCLE ACTIVITIES

(1) Support design and development in order to establish the inherent R&M of the design that is consistent with specified objectives (from conceptual studies) for a balanced design.

(2) Demonstrate specified R&M during the development phase.

(3) Ensure that the demonstrated (or specified) R&M levels are not appreciably degraded during production, are controlled throughout contract performance and are achieved in the field.

Accomplishment of these objectives requires a comprehensive and highly detailed program comprised of effective, systematic, and timely management activities, engineering tasks and controlled tests which meet the requirements of MIL-STD-785 and MIL-STD-470.

The essential R&M control elements and engineering tasks necessary to support design, development, demonstration and production of aviation systems that achieve actual field R&M levels consistent with the needs of the Army are:

(a) Performance of detailed R&M analyses and cost trade-off studies during the early design phase to aid in the achievement of a balanced design at minimum total cost of ownership.

(b) Definition and implementation of an effective management and control program. This program would directly enable R&M personnel to influence design, provide timely outputs consistent with major design and program decision points, and in general, provide the means to develop a system that meets cost effective objectives and requirements.

(c) Application of systematic and highly disciplined engineering tasks continually during the design phase. Their purpose is early identification and correction of problems which will force the design to be iterated as necessary, prior to the build-up of hardware.

(d) Early procurement, build-up, and reliability growth testing of critical components.

(e) Performance of R&M growth and demonstration testing during the development phase. This testing emphasizes failure analysis and corrective action and provides a test cycle that reflects the application environments, including mechanical stresses and climatic extremes.

(f) Implementation of a production reliability assurance program. This program must provide controls and procedures which allow a smooth transition from design and development to production without degrading reliability, and which emphasize "forced-defect" testing at critical stages in the equipment fabrication process.

3.3.1 Program Provision Definitions

This subsection of the guidebook defines basic provisions, within the framework of MIL-STD-785 and MIL-STD-470, which would form R&M programs considered applicable to the development and production of aviation systems and components and which meets Army procurement needs.

AR 70-1 defines three basic development options that exist to meet a specified need:

Option 1 provides for the purchase of existing commercial aircraft systems in order to obtain a low cost, quick-response capability for certain requirements. Advantages of this option include use of a proven design, reduced lead-times and minimal development expense. Possible

disadvantages associated with Option 1 include inability to meet R&M requirements, limited performance, parts availability, reduced control of model changes and increased logistic support requirements.

Option 2 provides for the procurement of modified versions of existing commercial aircraft. This option provides for use of the basic commercial configuration with modifications to meet certain specifications (e.g., towing, lifting, extended range, etc.). Possible advantages to this form of procurement are quicker availability and lower development cost than a new military design item. Possible disadvantages include the loss of integrity of the commercial product and the addition of unproven components and the compromise of mission capability.

Option 3 provides for the procurement of helicopters which are of military design. Within this option are two categories for system procurement: (a) existing development which is characterized by an existing TDP; ECO's which do not significantly impact schedule, require extensive requalification, or involve substantial redesign; a smooth transition to production which involves existing production facilities. (b) new development which involves a complete new design or changes to major components and major redesign of existing system. New development is characterized by the establishment of a program office, and preparation or restructuring of a TDP. The possible advantages of procuring a newly designed item are that the item can fully meet military requirements, that the design and configuration can be government controlled, and that the logistic support can be assured. Possible advantages of procurement of an existing design are the shorter lead times involved, the use of less costly PIP's to reach required performance objectives and the utilization of existing technology.

These options can be described in terms of sets of related R&M specifications and controls which correspond to varying levels of R&M. Three sets of R&M controls and specifications can be defined corresponding to system, mission and safety levels which are applicable to each option. The R&M control levels are defined as follows:

Level 1--<u>High reliability is a requirement for minimum unscheduled maintenance system reliability, mission reliability and flight safety</u>

Relates to reliability efforts and controls applicable to programs where the highest possible reliability is essential and strict requirements are imposed on system reliability, mission accomplishment and flight safety. Extensive specification requirements are given, including those for performance, production controls and testing which are consistent with a well defined, tightly regulated product.

Level 2--<u>High reliability is a requirement for mission reliability and flight safety</u>

Relates to reliability efforts and controls applicable to programs where high reliability is required for mission accomplishment and flight safety and normal system reliability is required. Program requirements and controls are defined to insure conformance within these constraints. Manufacturers must apply adequate material and process controls during critical production stages.

Level 3--<u>High reliability is a requirement for flight safety</u>

Relates to reliability efforts and controls applicable to programs where high reliability is required relative to flight safety considerations. Normal system and mission reliability are required where maintenance and replacement can be readily accomplished and down time is not critical. Components are generally of nominal reliability, e.g., per military standards, except those which are safety critical.

As shown above, Level 1 represents the most stringent R&M effort. The matrices given on the following pages (Figures 3-3 through 3-6) define the provisions, specifications and controls that comprise Level 1 relative to the three procurement options. Numerical values, based on experience factors, can be assigned to each level and used to assess and control the impact that reliability program provisions have on actual system reliability.

Figure 3-7 identifies Army aviation systems currently in the inventory or under development. This figure characterizes the procurement option and reliability level for each system, and shows the mission role for each aviation system listed.

3.3.2 Recommended Contractor Program

This section of the guidebook is intended to be used as an aid in the formulation of an aviation system contractor R&M program plan that will meet Army requirements. It should be noted that each development program must be structured and tailored to coincide with its specific hardware development option, and meet its specified level of reliability and maintainability. Figure 3-8 identifies the essential elements which would comprise an effective contractor R&M program for a newly designed aviation system that requires a full development program (per option 3B) and must meet the Level 1 R&M provisions (i.e., low probability of unscheduled maintenance and high probability of mission success and flight safety). A program per Level 2 or Level 3, as defined per Section 3.3.1, can be identified based on the elements given here.

The contractor program elements listed in Figure 3-8 provide the key tasks within a well controlled program. Further discussion of a few of the contractor program tasks, particularly those applicable to early development, are given in the following paragraphs. Section 3.4, following, provides specific guidelines applicable to all provisions that make up a development and production R&M program.

R&M management involves defining and assuring the effectiveness of the various R&M control elements planned for use

R & M Techniques		Option 1: Existing Commercial	Option 2: Modified Commercial	Option 3 A: Existing Military	Option 3 B: New Development Military
Management	Organization	1) R/M coverage during production	1) R/M coverage during design, development and production	1) Detailed emphasis on production aspects of R/M: • Failure Analysis • Production R Assurance • Data Collection • Reduction & Analysis • Procurement Control	1) Well staffed organization covering all aspects of R/M including detailed coverage of: • R/M Management • Design Analysis • R/M Analysis • Component Engineering • R/M Testing & Demonstration • Failure Analysis • Production Reliability Assurance • Data Collection Reduction & Analysis
	Control Tasks	1) Emphasis on internal control elements focusing on flight safety provisions.	(same)	1) Full and detailed R/M plan that defines all control elements, key personnel and their responsibilities, and interrelationships. 2) Complete list of control tasks including reference procedures for implementation, manhours for each task and person responsible for implementation. 3) Definition of R/M milestones--milestones included in overall program schedule. 4) Established methods for providing R/M data and information to design, production, etc., i.e., proven methods for forcing R/M program activities to impact design and production. 5) R/M training program.	(same)
	Subcontractor & Supplier R/M Programs	1) Qualify vendor via survey & audit to manufacturer's requirements. 2) Approved supplier list maintained and defined on procurement documents. 3) Major component suppliers require certification. 4) Purchase orders for major subcontractor items should require: • R/M planning provisions	(same)	1) Qualify vendor via survey and audit to MIL-STD-785 requirements. 2) Approved supplier list maintained and defined on procurement documents. 3) Surveillance and source inspection at parts suppliers or major subcontractors (full time residence by Quality, part time by Reliability). 4) Purchase orders for major subcontractor items will require: • Reliability Program Plan • Closed-Loop Failure Reporting System • Failure Analysis • Reliability Demonstration Test as required to the specified MTBF per MIL-STD-781B. • Engineering tests as required.	(same as A) 5) Reliability predictions 6) Failure mode & effects analysis.
	Program Review	Not performed	Same as Option 3B-governed by internal contractor operating procedures	Not performed	1) Formal reliability program reviews for major subcontractor items at the end item & item unit levels. Update as necessary. 2) As required by procuring activity in program schedule

Figure 3-3

PROGRAM MATRIX -- MANAGEMENT

R & M Techniques		Option 1 Existing Commercial	Option 2 Modified Commercial	Option 3 A Existing Military	 B New Development Military
Design Evaluation	Design Analysis	Not performed	Not performed	Not performed	1) Probablistic Design (SSI) 2) Fatigue Analysis (PSN) 3) Mechanical systems analysis using Bayesian failure distributors. (Computer Aided Design) 4) Electrical circuit analysis 5) Design analysis on all circuits 6) Transient and thermal analysis 7) Monte Carlo analysis
	R/M Apportionment & Prediction	Not performed	1) Math model prepared on functional basis for equipment, component or replaceable units.	Not performed	1) Preliminary per RADC Notebooks, MIL-HDBK-217 or other historical data sources 2) Update as necessary to incorporate significant design changes
	Component Reliability	1) Maximum use made of existing specs, test & qualification data, manufacturing methods & in-process controls. 2) Components of nominal reliability Minimum acceptance criteria as imposed to ensure a low probability that devices outside the specified limits will be included in lot shipments.	1) Compile and issue Preferred Parts List; keep current. Minimal testing to supplement prior knowledge and reduce risk of disqualification 2) Components of nominal reliability. Minimum acceptance criteria as imposed to ensure a low probability that devices outside the specified limits will be included in lot shipments	1) Compile & issue Preferred Parts List. 2) Maximum use made of existing specs, test & qualification data, manufacturing methods & in-process controls. 3) Review non-standard data 4) Compile & issue Approved Materials & Process lists.	1) Mandatory prats/components list compiled and issued by a Parts Control Board-based on selective evaluation typical device performance under dynamic conditions, basic design, materials & manufacturing methods. 2) Extensive specification requirements, including both performance and production controls. Manufacturing methods in-process controls, and testing are consistent with a well defined, tightly regul-ted product. 3) Submit non-standard date 4) Compile & issue Approved Materials & Processes List
	Failure Mode & Effect Analysis	Not performed	1) FMEA performed to major component level for catastrophic failure modes.	Not performed	1) FMEA at end item equipment, component, and part levels per directives for all significant failure modes.
	R Critical Items	Same as Option 3A	Same as Option 3B	1) Review existing list of critical items; revise as necessary	1) Maintain a reliability critical item list; update monthly.
	Effects of Storage, Shelf-Life, Packaging Transportation, Handling & Maintenance	Same as Option 3A	Same as Option 3B	1) Review effects of storage, transportation & handling on all critical parts, units & end items. 2) Establish procedures for reducing R degradation for selected critical items as indicated	1) Evaluate environments for storage, transportation & handling of all critical parts, units & end items. 2) Establish formal procedures and instructions for reducing reliability degradation for selected critical items.
	Design Review Data	Not performed	Not performed	Not performed	1) Supply reliability information for formal review at system, equipment item and component levels. Update as required by CDRL

Figure [illegible]

PROGRAM MATRIX -- DESIGN EVALUATION

R & M Techniques		Option 1	Option 2	Option 3	
				A	B
		Existing Commercial	Modified Commercial	Existing Military	New Development Military
Production Reliability	Transition from Development	1) Develop production reliability test and control plan covering receiving inspection, in-process testing, screening and burn-in and final testing.		Same as Options 1 and 2 2) Plan requires government approval	
	Receiving Inspection	1) Inspect critical parameters as defined per engineering procurement documents part activities and critical parts list. 2) Maintain adequate inspection instructions, criteria, test equipment, personnel, etc., to assure high inspection efficiency. 3) Perform 100% inspection of safety or reliability critical parameters.		Same as Options 1 and 2	
	In-Process Testing	1) Test/inspect critical parameters or dimensions at appropriate points in the assembly process based on instructions derived from engineering documents. 2) Assure existence of adequate procedures, equipment, inspection criteria and personnel to assure high inspection efficiency. 3) Perform 100% inspection of safety or reliability critical parameters.		Same as Options 1 and 2	
	Screening & Burn-In	Not performed	Not performed	1) Review existing methods & procedures revise or incorporate screens as necessary.	1) Tests designed to uncover defects at the major assembly, component or system level. 2) Consist of operational stress/limited stress tests to uncover design weakness, workmanship errors or weak parts. 3) Most useful in uncovering time-dependent (reliability) type defects.
	Final (Acceptance) Testing	1) Conducted on all systems leaving production. 2) Designed to assure proper functioning of all elements. 3) Performed per written test procedure.		Same as Options 1 and 2	
	Final Test Procedure	1) Provides specific documented coverage of acceptance criteria. 2) Contains detailed check lists for visual, mechanical and electrical tests and inspections. 3) Identifies critical parameters or inspections. 4) Plan requires government approval. 5) Provides detailed methods, defines required test equipment, fixtures and step by step instructions for performing tests and inspections.		Same as Options 1 and 2	
Data Collection	Analysis & Reduction	1) Establish specific mechanisms for collecting and reducing data from factory and test operations. 2) Identify data items of interest; plan usage of data systems, e.g., TAERS/TAMMS, to fulfill data feedback requirements. 3) Establish data formats and other documents for factory data collections.		Same as Options 1 and 2	

Figure 3-5

PROGRAM MATRIX -- PRODUCTION RELIABILITY & DATA COLLECTION

	R & M Techniques	Option 1 Existing Commercial	Option 2 Modified Commercial	Option 3 A Existing Military	 B New Development Military
Testing & Demonstration	Development Testing	Not performed	1) Environmental test performed as applicable	Not performed	1) Environmental tests performed per MIL-STD-810, 781, etc. 2) Reliability growth testing per MIL-STD-781 performed on development units as necessary to reach desired level of reliability. 3) Assure spares are available to sustain testing. All spares to be subject to the same conditioning tests as the prime equipment. 4) Special reliability tests on critical equipment items/components.
	R Test Plans	Not performed	1) Prepare integrated test plan covering "forced defect" testing during fabrication of test units, reliability growth testing & reliability demonstration. 2) Test plan must define failure and success criteria.	Not performed	Same as Option 2 3) Plan must be based on MIL-STD-810, 781, etc., and requires government approval.
	R Demonstration	Not performed	Not performed	1) Test per MIL-STD-781 B, Para. 5.2 and Applicable Test Level. Assure the spares are available to sustain testing.	
	R Test Records & Recording	Not performed	Not performed	1) Adequate test records including operating tiem, failure data, test logs, etc., and reporting as required per CDRL data items.	
Failure Reporting Analysis & Corrective Action	Failure Reporting	For all failures which occur during: • Acceptance tests	• Demonstration, production & final acceptance tests.	For all failures which occur during: • Demonstration, production & final acceptance tests.	• Demonstration, production, & final acceptance tests. • Development • R growth
	Analysis	• Analyze and close out all reported failures.			
	Corrective Action	• Initiate corrective action and follow-up on all reported failures.			
	Failure Summary	• Submit failure report summaries to all cognizant activities.			

Figure 3-6
PROGRAM MATRIX -- TEST/DEMONSTRATION & FAILURE REPORTING

AIRCRAFT SYSTEM	CURRENT LIFE CYCLE PHASE	MISSION	DEVELOPMENT OPTION	RECOMMENDED* RELIABILITY LEVEL
HELICOPTERS				
ATTACK				2
AH-1 COBRA	DEPLOYMENT	GUNSHIP (ATTACK)	3A	
AH-IQ ICAP	DEVELOPMENT	GUNSHIP (ATTACK)	3B	
AH-56 CHEYENNE	DEVELOPMENT (CANCELLED)	GUNSHIP (ATTACK)	3A	
AAH-ADVANCED ATTACK HEL.	DEVELOPMENT	GUNSHIP (ATTACK)	3A	
CARGO				1
CH-34 CHOCTAW	NOT ACTIVE IN U.S. ARMY	CARGO	3A	
CH-47 CHINOOK	DEPLOYMENT	CARGO	3A	
CH-54 TARHE	DEPLOYMENT	CARGO	3A	
HLH HEAVY LIFT	DEVELOPMENT	HEAVY LIFT CARGO	3B	
UTILITY				1
UH-1 IROQUOIS	DEPLOYMENT	UTILITY	3A	
UTTAS	DEVELOPMENT	UTILITY (TROOP TRANSPORT)	3B	
214-A IRANIAN	DEVELOPMENT	UTILITY	3B	
TRAINER				3
OH-13 SIOUX	DEPLOYMENT	TRAINER	3A	
OH-23 RAVEN	DEPLOYMENT	TRAINER	3A	
TH-55 OSAGE	DEPLOYMENT	TRAINER	3A	
OBSERVATION				2
OH-6 CAYUSE	DEPLOYMENT	OBSERVATION	3A	
OH-58 KIOWA	DEPLOYMENT	OBSERVATION	2	

Figure 3-7

RELIABILITY CHARACTERIZATION OF ARMY AVIATION SYSTEMS

AIRCRAFT SYSTEM	CURRENT LIFE CYCLE PHASE	MISSION	DEVELOPMENT OPTION	RECOMMENDED RELIABILITY LEVEL
FIXED WING				
OBSERVATION				2
O-1 BIRD DOG	DEPLOYMENT	OBSERVATION	2	
VTOL & STOL				2
OV-1 MOHAWK	DEPLOYMENT	SURVEILLANCE PHOTOGRAPHY	3A	
UTILITY				2
U-1 OTTER	DEPLOYMENT	GENERAL UTILITY	1	
U-6 BEAVER	DEPLOYMENT	GENERAL UTILITY	1	
U-8 SEMINOLE	DEPLOYMENT	GENERAL UTILITY	1	
U-9 AERO COMMANDER	DEPLOYMENT	GENERAL UTILITY	1	
U-10 COURIER	DEPLOYMENT	GENERAL UTILITY	1	
U-21 UTE	DEPLOYMENT	GENERAL UTILITY	2	
TRAINER				3
T-41 MESCALERO	DEPLOYMENT	TRAINING	1	
T-42 COCHISE	DEPLOYMENT	TRAINING	1	

*All recommended Helicopter Reliability levels are specified by aircraft type (i.e., Utility, Cargo, Attack, etc.). The recommended levels are based on the following rationale:

- Helicopter systems with critical combat missions are designated as level 2.
- Training aircraft are designated level 3 due to their limited number and since their missions are of a non-critical nature
- Large Helicopter fleets are designated level 1 due to the large maintenance burden they impose on the Army.

Figure 3-7

RELIABILITY CHARACTERIZATION OF ARMY AVIATION SYSTEMS (continued)

Management--provides the organization, planning, control provisions, documentation, and definition necessary to carry out R&M tasks.

R&M Apportionment--indicates the methods and results of subdividing system level reliability requirements down to component and part levels of assembly.

R&M Prediction--provides the modeling details, data base and results during the design and development process.

Maintenance Concept--provides definition of the scope of maintenance activities at field sites, intermediate facilities and depot locations. Included are provisions for fault isolation, AGE, skill requirements and periodic maintenance inspections and overhaul.

Failure Mode Analysis--provides an analytical part-by-part method to determine the consequences of potential failure on system operation.

Component Control & Standardization--provides effort to select, specify and control all "critical" mechanical, electronic and electro mechanical parts and components. Includes vendor R&M control provisions.

Design Review--provides the framework for formal evaluation of contractor effort with participation of cognizant contractor and government personnel and includes PDR, CDR and mock-up reviews.

R Growth Testing--provides the method by which defects are discovered and corrected during a test program which ultimately leads to system maturity.

R&M Demonstration Test--provides the methods for showing that that system complies with numerical R&M requirements.

Failure Analysis--provides the methods and techniques to determine causes of observed defects and report these findings for subsequent action.

Forced Defect Testing--provides methods for non-destructively forcing-out latent defects prior to field operations.

Reliability Assessments--provide methods for determining the actual reliability based on system testing or field use data.

Data Collection & Feedback--provides the mechanism for collecting operational, maintenance and installation data for feedback to the data base.

Figure 3-8

RECOMMENDED CONTRACTOR PROGRAM ELEMENTS

during system development. This, in general, involves reviewing the SOW and the preparation of an R&M program control plan. The control plan must detail the approach, criteria and procedures to be followed to meet the objectives of the development program as specified in the SOW, MIL-STD-785 and MIL-STD-470. The control plan must recognize that, in order to achieve an actual field reliability that approaches the predicted reliability, the thrust of the R&M program must be: (1) to emphasize early R&M analysis and prediction, and the use of accurate and detailed models that account for design and field application factors; (2) to force out defects through an aggressive reliability growth program; and (3) to measure reliability under environmental conditions which duplicate field conditions. This emphasis must be projected into the control plan.

In general, contractor R&M program management encompass three areas:

(a) organization,

(b) management procedures,

(c) engineering analysis and control programs.

The R&M organization must have direct access to program management and must have an effective relationship to design, manufacturing, procurement, quality control, cost and other organizational functions with separate responsibilities and authorities. It must be comprised of a highly effective team of specialists with experience in all R&M areas. Key personnel must be committed full time to the development program.

The management procedures must provide a viable mechanism for R&M personnel to influence design directly. The intent is to determine, for example, if reliability is a serial element in the design process (with sign-off authority), or if reliability is entered into the design process indirectly via other organizational functions (design, cost, etc.).

The R&M engineering tasks, analyses and control elements must be adequately described, scheduled and properly timed such that they coincide with major project design points. These R&M activities and their outputs must be incorporated in the overall project schedule and must constrain applicable decision points.

Among the R&M engineering analyses and control activities that must be included in the program plans are the following:

- R&M allocations, predictions and assessments (particularly modeling details and data base validity),
- Failure mode analysis,
- Component control program (covering selection approval, standardization, specification and application),
- Design review,
- Reliability growth and R&M demonstration,
- Design standardization,
- Failure reporting, analysis and corrective action,
- Manufacturing controls (particularly programs for improving reliability involving forced defect and overstress testing).

R&M Apportionment involves the subdivision of equipment reliability requirements (or goals) into the various major items that comprise the system. These apportionments become, in turn, design requirements for the individual equipment items. An apportionment study, to serve the needs of the bulk of the impending design effort, must be completed shortly after contract award. The apportionment study allocates failure rates or repair rates quantitatively to the lowest practical functional level. Ideally, the contractor's apportionment study should show an increment in reliability (MTBF) or maintainability

MTBMA that approaches the predicted MTBF. All analytical prediction efforts must be performed with the ultimate field use in mind.

Design Reviews involve evaluations of performance, reliability, maintainability, and various other characteristics of the system at major design and testing milestones. The contractor's own internal design review program must be geared to ascertain that methods have been established which provide for review of all system elements down to the component level; that the program includes subcontractor's design review activities; that it adequately defines the participants and their responsibilities; and that it describes the deficiency-follow-up control procedure. In addition, design review procedures must include a detailed and comprehensive check list and criteria against which the design can be evaluated. The check list must be relevant to the design phase under review.

Design reviews provide the means for the Army's formal assessment and monitoring of the contractor's design effort and generally coincide with major program milestones (PDR and CDR).

Failure Mode Analyses involves a part-by-part analysis to determine system and/or component effects when considering all significant failure modes. The analysis is intended to:

- relate parts, assemblies, or functions to their failure effect,
- determine quantitatively the occurrence probability of the failure effects,
- determine failure mode criticality,
- provide a basis for corrective action well in advance of equipment fabrication,
- aid in the generation of test plans and procedures,
- aid in the analysis of failures

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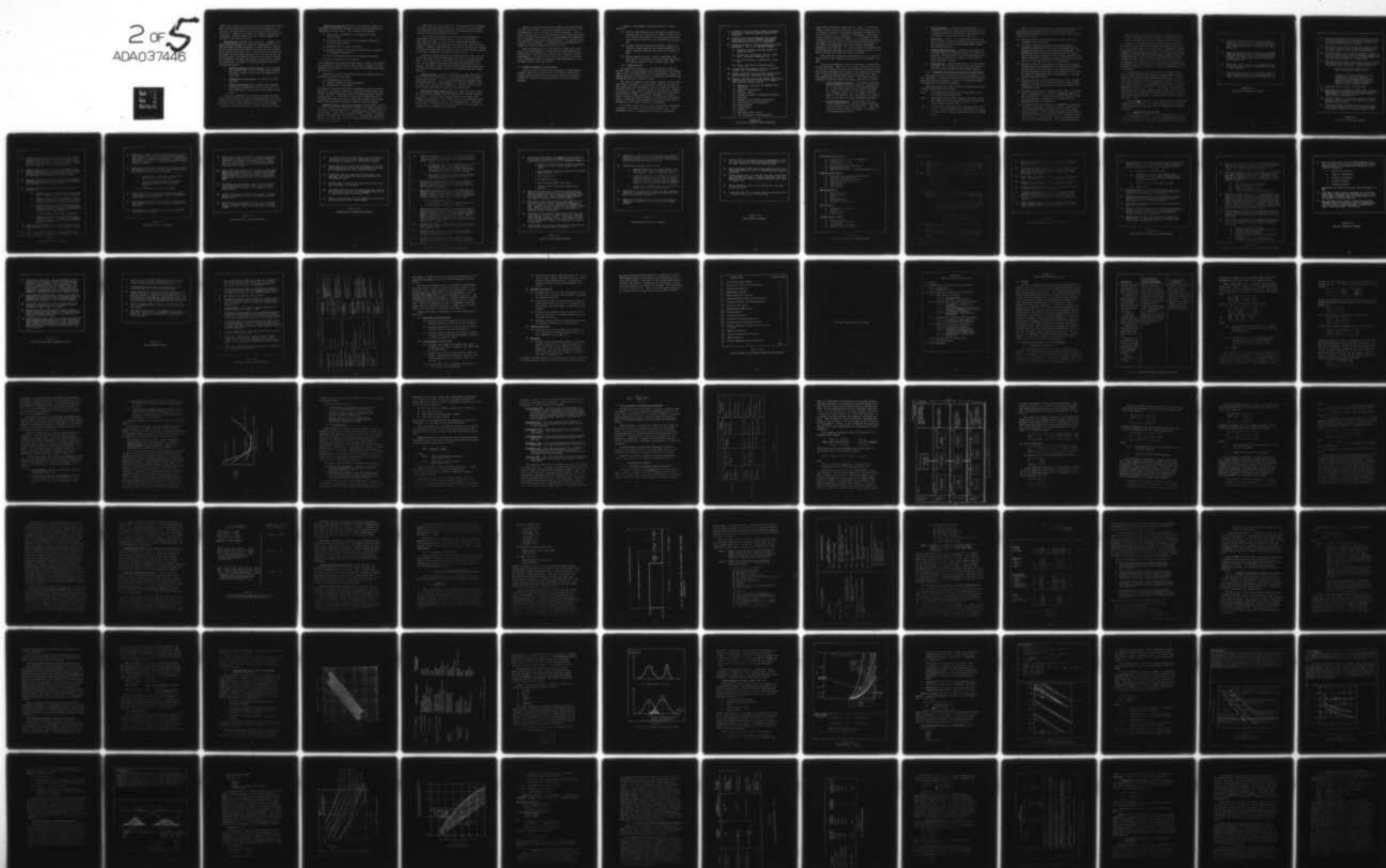

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(MTTR) over and above a strict subdivision of numerical requirements at the given level and which serve as design goals. In addition, the apportionment study should be based on system criticality, complexity of design and function, operational use environment, previous experience with similar equipment and relation to the state-of-the-art.

R&M Prediction involves identifying the equipments' reliability and maintainability parameters quantitatively (e.g., MTBF and MTTR) through development of system models, identification of applicable distribution functions and use of appropriate failure and repair rates. Contractors must assure that the models, distributions and input data used account for the mission profile, environmental application stresses, maintenance conditions and other operating/non-operating use factors. To be effective, contractor's predictions must reflect the following rationale:

- Specific purpose of the prediction, e.g., to establish inherent R&M, to aid in design-based tradeoff decisions, and/or to help force out engineering design flaws.
- Credibility of data sources and contractor empirical data.
- Adequate methodology which clearly shows modeling assumptions, configuration basis, and level of detail applicable to the status of the design at that point.

To be fully cognizant of the impact of field use conditions, and to reflect non-ideal maintenance/supply conditions, prediction efforts must recognize the failure and repair cycle expressed by mean-time-between-maintenance-actions (MTBMA). Furthermore, R&M efforts must be directed toward achieving an

<u>Failure Mode Analyses</u> involves a part-by-part analysis to determine system and/or component effects when considering all significant failure modes. The analysis is intended to:

- relate parts, assemblies, or functions to their failure effect
- determine quantitatively the occurrence probability of the failure effects
- determine failure mode criticality
- provide a basis for corrective action well in advance of equipment fabrication
- aid in the generation of test plans and procedures
- aid in the analysis of failures

To be effective, these analyses must detect, analyze and evaluate all significant failure modes at major project phases, and must convey their findings in time to be used at corresponding project decision points.

Contractor failure mode analyses must be prepared using the following criteria for guidance:

1) thoroughness of analysis
2) impact of modes on system operation
3) probability of occurrence

In addition, these analyses must be assessed in terms of system capability (or reduced capability) under the failure modes identified, and when considering alternate operating modes, mission alternatives, etc. Contractor's plans for corrective action, resulting from identification of modes which reduce system capability below acceptable minimum standards, must be defined.

<u>Component Control and Standardization</u> involves effort directed to select, specify and control all critical or primary mechanical, electrical or electromechanical components used or planned for use in the system. This effort includes methods to secure necessary approval for components for system use. Consequently, detailed effort to justify, test, and assure quality form an extensive part of the control process.

Contractor plans and efforts in this area must be formulated to provide adequate definition of all facets of critical component specification and qualification, including special controls covering source and incoming inspection.

The preceding paragraphs have dealt with the design or development phase of a given system. This is by far the most important time to establish an effective R&M program as these qualities are not something that can be put in as an afterthought. However, sound R&M practices must be carried out through the production and operation phase as well, or any benefits gained in the early stages of the program could be lost.

During the production phase assurances must be made that the system will meet the R&M requirements set for it in the program plan. The difficulties in assuring that the requirements are met, lie in assembly processes and design changes made to the system. Therefore, during the production phase, R&M efforts must be directed toward Quality Control, and modification and change control.

<u>Quality Control</u> consists of sampling and inspecting components or parts to assure that they are not defective in construction and/or material. Also, the workmanship and manufacturing techniques employed in the assembly of a system or product, must be consistent, and of high standards to realize the full reliability and maintainability designed into the system.

<u>Modification and change control</u> only come into effect when for some reason, changes have been made to the original design of the system. In this case, the manufacturer must consult the designer to ascertain if the changes made to the system will meet the R&M requirements set for it in the program plan. Therefore, in all cases, to insure that the R&M planned for is attained, the designer must be consulted for approval.

During the operational phase the major tasks accomplished are verification that the R&M requirements have been met, and recommendations for improvement of future equipment. This is done by taking data on the effectiveness of the first production run of equipment, and evaluating its performance in comparison with the predicted or prescribed parameters. If the system does not meet the requirements, recommendation for improvement or change are made for subsequent production runs.

When the production of a helicopter or subsystem is complete, and the equipment is being used for field operations, further data will be taken to insure that it has met its R&M requirements. This data will be taken in the form of Unsatisfactory Equipment Reports, Equipment Improvement Reports, and the Army failure reporting systems.

3.4 Program Management and Monitoring

This section of the guidebook discusses the R&M program elements identified in Figure 3-8, and provides evaluation review points and monitoring guidelines which can be used by AVSCOM as a basis for managing aviation systems procurement programs.

In general, R&M mangement and monitoring must include effort to:

(1) Perform trade-off and cost effectiveness studies and formulate detailed requirements (SOW) in terms of program elements and numerical specifications which are cost effective and have a high probability of achievement.

(2) Evaluate contractor proposal documents, control provisions, program planning and technical expertise to select the most qualified contractor with respect to R&M.

(3) Monitor ongoing projects, conduct independent R&M assessments, participate in design reviews and advise the project manager in matters which impact R&M.

3.4.1 R&M Trade-offs

As indicated in Section 3.2, the R&M and cost trade-off studies (Item 1) are performed during design concept and validation to aid in the achievement of a balanced design. Figure 3-9 defines activities and work effort that would be involved in performing R&M and cost trade-off studies.

Note that performance, gross weight, payload, volume, shaft horse power, reliability, maintainability and cost are some of the significant system parameters subject to detailed study and trade-off decisions. For this process to be effective, analytical methods are needed for systematically generating and evaluating alternate design concepts and approaches, in order to select a system or component design that best meets performance, mission, reliability, maintainability and other system needs or constraints at the lowest total cost of ownership.

It should be noted that for trade-off purposes, performance is normally evaluated at several discontinuous levels. Each performance level is simply defined relative to functional

(1) Standardize the data base in order to provide a baseline for comparing competing design configurations.

(2) Provide standardized definitions for failure consistent with safety, mission, and unscheduled maintenance reliability requirements.

(3) Establish credibility of early predictions and/or assessments. This is established through:

(a) Reliability Models--detailed enough for trade-off studies.

(b) Assumptions--environment (ground, flight, etc.), component technology, etc.

(c) Application factors, temperature, stress, etc.

(d) Other Ground Rules--component quality.

(4) Provide R&M input numerics for cost trade-off studies (cost-of-ownership models).

(5) Define reliability cost sensitive factors (from cost-of-ownership comparisons and studies).

(6) Monitor, evaluate and control special R&M projects which include trade-off studies with respect to cost sensitive factors such as:

(a) Mechanical, electrical and thermal stress (derating),

(b) Component substitution,

(c) Component quality,

(d) Component/equipment screening and burn-in,

(e) Redundancy

(f) Packaging (environmental resistance),

(g) BITE (Built-In Test Equipment),

(h) Modularization,

(i) Accessibility,

(j) Alignment,

(k) Maintenance skill levels,

(l) MGE (Maintenance Ground Equipment).

Figure 3-9

R&M AND COST TRADE-OFF STUDY ACTIVITIES

needs and/or determined through special studies. In contrast, weight, volume and shaft horse power can be regarded as a "cost" (or penalty) incurred in designing performance or R&M levels into the system; that is, increases in performance or R&M levels usually require increases in weight. It is reliability, maintainability and cost that are the sensitive variables which have continuously varying levels with wide extremes that depend on all facets of an equipment life cycle--design, development, manufacture and field use. It is these sensitive variables that involve modeling techniques in order to provide estimates in the detail necessary for effective trade-off studies.

R&M trade-offs involve the determination of cost changes as R&M is varied from a baseline configuration and development program.

The actual performance of these trade-offs is accomplished as outlined below. Note that this is both a step-wise and iterative process whereby new data is factored into the process until the desired refinements are achieved. This process will utilize cost, reliability and maintainability data drawn from a data base established for the trade studies. The steps involved in performing trade-off studies are broadly described as follows:

1. Perform Preliminary Analysis. (a) define appropriate trade-off measures such as reliability, maintainability, or time related probability of system operation, (b) define the trade-off criteria such as minimum cost, minimum schedule, etc., (c) define the level of effort to be applied to the trade-off process consistent with the level of system definition available.
2. Perform Design Analysis. Further define the constraints associated with specific system or hardware items and support system characteristics. Define the limitations between which increments in reliability and maintenability may vary.

3. <u>Define Parameters</u>. Establish the parameters of a standard or "baseline" design which just meets all requirements and which establishes a starting point for all parameters of interest during trade-offs.

4. <u>Gather Data</u>. Collect, sort and validate system data and, to a lesser extend, component and part level data from multiple sources including TAERS/TAMMS, RAMMIT and system contractors.

5. <u>Perform Trade-Off Studies</u>. Generate and evaluate design approaches for R&M which satisfy the trade-off criteria. Generate sensitivity curves which show the break-points for R&M with respect to cost, and for given performance inputs.

6. <u>Refine Studies</u>. Apply design details, as they become available, for refinement of the trade-off studies so that the optimum design approach becomes apparent.

3.4.2 Evaluating and Monitoring Contractor's R&M Program

This section provides detailed criteria and guidelines for use, by AVSCOM, in evaluating and monitoring contractor development and production programs. Section 3.4.3 provides methods for evaluation of contractor proposals.

There are three major steps involved in evaluating and monitoring a contractor's R&M program:

Step 1 establishing R&M review points that provide a basis for evaluation and monitoring,

Step 2 developing criteria from a review of the SOW, system spec, CDRL items and conceptual studies to form a detailed program baseline, and

Step 3 applying the review points and criteria against contractor's planned R&M efforts to determine its overall effectiveness and results during the course of the R&M program.

Some of the key considerations that must govern AVSCOM's ongoing contractor management activities and as such must be stressed when formulating specific project review points and criteria are as follows:

(1) The relationship of the R&M program to other project requirements must be defined.

(2) A formally organized program with central management, a documented program plan, and separate accountability for program resources must be structured and implemented. The R&M program must be negotiated together with the negotiation of the overall project contract (rather than after contract execution). A realistic program that delineates scope and cost of all R&M efforts must be established.

(3) Periodic reviews of the program are required which provide for revisions of the program plan, if necessary, depending on the results of the reviews. Since these reviews are jointly conducted by the Army and the contractor, they serve as a means of implementing the recommendations of the R&M program evaluation effort.

(4) The prime contractor must maintain control of his own R&M effort as well as that of subcontractor and supplier R&M programs, and must determine their effect on reliability of the overall system.

(5) All project data must be accessible and visible to the Army and its representatives, including independent R&M assessment contractors. In order to provide for the most convenient accessibility, a central file or data center for documentation must be established.

(6) The project must be covered by one integrated test program (including development, reliability growth, demonstration and forced-defect testing) instead of separately managed testing programs. This requirement prevents both duplications and omissions in testing and, also, provides a single test baseline in parallel with a closely interrelated program of reliability assessment. This approach emphasizes

the intimate tie-in of the reliability assessment effort with the requirements of the project, and underscores its role as an input to the various project decision points.

Figures 3-10 through 3-29 present review points (18) that can be used as the basis for contractor evaluation and monitoring. These review points are intended to correspond to the R&M program elements identified in Figure 3.8, and as such provide evaluation criteria when considering a full military development program (Option 3B) with the highest R&M requirement (level 1). In addition, these review points can be used as the basis for evaluating other procurement options and levels of reliability. Included for each review point are evaluation considerations and monitoring criteria with respect to individual R&M tasks and control elements.

It should be noted that review points 1 through 17 are devoted to R&M engineering and control activities while review point 18 covers overall R&M organization and control. In addition to the technical criteria associated with each task, certain aspects associated with management and control are covered. Each contractor must be evaluated and monitored with respect to management relative to each task. In addition, the managerial aspects and basic premises imbedded within these tasks must show the interaction of each task with other tasks within the framework of the overall R&M plan, and how each task impacts detail design activities.

Review point 18 addresses itself specifically to overall R&M organization and control. It stresses factors within the areas of R&M organization, methods of control, planning and reporting activities.

3.4.3 Proposal Evaluation Guides

As indicated in Section 3.2, a key evaluation effort is contractor proposal evaluation. Effective accomplishment of proposal evaluation will not only select the most qualified contractor

- Overall allocation methodology shall be based on criticality, complexity of design and function, operational use environment, previous experience with similar equipment and relation to the state-of-the-art.

- Specific allocations shall be based on conceptual goals and predictions and shall possibly include a further improvement factor which challenges designers; e.g., improvement factor could be 125% of predicted value.

- Allocations shall be made to the component level and provide design goals for components and higher level assembly.

- Allocations are a one-time study effort completed shortly after the start of the detail design phase; submittal should be well in advance of PDR.

Figure 3-10

RELIABILITY ALLOCATION CRITERIA

- Effort shall consist of analytical estimates of system R, MTBF and MTBMA based on mathematical models, failure rates and stress/environmental factors and underlying statistical distribution of failures.

- Predictions shall include factors for mission profile, duty cycle, operating and non-operating failure rates and known applicable failure modes and mechanisms.

- Prediction effort shall establish inherent reliability to aid in design based trade-off decisions, provide criteria for the starting point of reliability growth testing, and foster elimination of design flaws.

- Prediction efforts shall support the design of a system that exhibits the inherent MTBF resulting from conceptual design trade-off studies. Further criteria are:

  - system (or operating mode) failure is a direct reflection of part failure.

  - reliability is determined from a series arrangement of parts or components (except where redundant design has been employed or where engineering analysis shows that failure does not degrade performance beyond acceptable limits).

- Techniques shall be based on MIL-STD-756A.

- Data bases for the prediction effort shall consist of RADC notebooks (electronic and non-electronic) RAMMIT, TAERS/TAMMS and contractor empirical data (other sources require Army approval).

- Prediction effort is an iterated process--initially based on gross part counts and subsequently based on detailed stress analyses.

- Scheduling should show predictions as a continuous effort during detail design with predictions updated periodically; submittals correspond to PDR and CDR.

Figure 3-11

RELIABILITY PREDICTION CRITERIA

- Analysis shall be a part-by-part (and possibly a failure-mode-by-failure-mode) analysis to determine the consequences of failure on system reliability, mission success, and flight safety which relates parts, components and functions to their failure effects.

- Analysis shall be based on data and information from design configurations, components engineering and part failure rates resulting from prediction studies, relevant historical information and earlier analyses.

- Analysis shall quantitatively determine the probability of modal failure for each mode identified and which allows ranking by numerical probability.

- Results of analysis shall be used to accomplish the following:

  - provide input to reliability predictions and aid in defining corrective action priorities.
  - identify critical parts, assemblies, parameters, and characteristics that can be used as basic criteria for production inspection.
  - establish corrective action criteria in advance of equipment fabrication without early large scale testing and aid in the generation of test plans and procedures.
  - provide failure-rate-by-mode distributions.
  - provide basic data for safety analysis and ranking of safety critical parts, assemblies and their failure modes for design on other corrective action.

- Analysis shall be updated periodically, based on data from failure analysis and other data collection activities.

- Effort is performed continuously during design iterations; submittals correspond to PDR and CDR.

Figure 3-12

FAILURE MODE ANALYSIS CRITERIA

- Contractor's plans shall provide definition as to what constitutes a repair action and the scope of maintenance activities planned for execution by organizational, intermediate and depot repair personnel. Contractor's approach to periodic or scheduled maintenance activities should be included.

- Contractor's maintenance concept shall state the scope and character of fault isolation and post-repair checkout activities including the following:

    - requirements for AGE need to support the system at each level of repair.

    - amount of ground operating time needed to perform preflight and post-repair checkouts.

    - personnel skill level requirements.

- Plans shall describe the methods and criteria established by which the maintenance concept is translated into hardware design features.

- Scheduling shall show the finalization of the maintenance concept during the early stages of the detail design effort.

- Definitions of the maintenance concept are submitted and finalized at the PDR.

Figure 3-13

MAINTENANCE CONCEPT CRITERIA

- Contractor's plans shall show how they quantitatively assign repair times (or MTTR) to systems, components, and levels of assembly corresponding to the repair activities performed at the organizational, intermediate and depot levels of maintenance and which provide goals for designers.

- Each repair time assigned shall include an improvement factor over and above a strict subdivision of system MTTR requirements, which forces emphasis and provides goals during detail design activities. (Improvement factors could possibly be based on a 25% reduction in MTTR).

- The results of the allocation shall be used to generate M demonstration and test plans, provide design goals and indicate marginal areas requiring concentrated effort.

- Specific allocations of MTTR shall account for anticipated repair frequency based on system and component failure rates.

- Allocations for maintainability are a one time study which is completed shortly after the start of detail design activities; submittal should be well in advance of PDR.

Figure 3-14

MAINTAINABILITY ALLOCATION CRITERIA

- Predictions should provide a quantitative evaluation of the design in terms of MTTR, repair rates and other statistical $\underline{M}$ parameters for each level of repair.

- Predictions shall indicate the feasibility of meeting system MTTR objectives and shall provide an assessment of the probability of correct fault indication.

- Predictions shall be supported by maintenance level diagrams, work factors and other data determined via maintenance analysis.

- Analysis shall identify areas requiring periodic cleaning, adjustment or replacement.

- Predictions shall be used to define preventive maintenance intervals, identify time replaceable items and aid in logistics/supply provisioning (MEADS).

- Results of predictions shall be submitted corresponding with major review points--PDR and CDR.

Figure 3-15

MAINTAINABILITY PREDICTION CRITERIA

- Contractor component control and standardization effort shall be directed to select, specify and control all critical mechanical, electronic and electro-mechanical parts. Further criteria are:

  - An Army/contractor part approval cycle shall be established, (e.g., which functions per MIL-STD-891 and/or an equivalent function of this nature) to assure component control which is compatible with Army aviation programs.

  - Part control activities shall provide continuous effort to minimize numbers and types of parts and components used.

- The selection process shall include design evaluation, reliability history review, construction analysis, failure mode and effects analysis and cost effectiveness studies as necessary.

- The control effort should include the development of meaningful procurement specifications which, when completed, reflect a balance between design requirements, QA and reliability needs consistent with apportionment studies and vendor capabilities and which cover:

  - lot acceptance testing,
  - QA provisions (including incoming inspection),
  - qualification testing, if required.

- Contractors component qualification approach should include detailed and formal submittal of data to support approval requests (data to be either statistical test data or analytical data for components where similarity exists or a combination of these two types). Note: Those components that require formal statistical test data for qualification should be entered under critical item control. (Figure 3-17)

- Contractors component control should indicate the maximum allowable (design application) stress levels for each component type.

- Contractor shall establish vendor control program, audits of vendor processes, associated documentation and needs for source inspection.

- A continuous component improvement effort should be provided which emphasizes state-of-the-art physics of failure techniques combined with controlled testing programs.

Figure 3-16

COMPONENT CONTROL & STANDARDIZATION CRITERIA

- Contractors plans shall list initial critical items and include parts, equipment/components, and other items considered critical from any of the following standpoints:

    - perform critical functions relative to mission success and flight safety (flight safety critical),
    - are reliability sensitive (from early R studies, apportionments, etc.),
    - have limited life,
    - are high cost items,
    - have long procurement lead times,
    - require formal statistical qualification testing

- Plans shall provide for critical item identification, control, special handling and shall identify critical item characteristics to be inspected or measured during incoming inspection. Methods include MRB procedures, traceability of material and periodic audits.

- Plans shall cover rules for early procurement of critical parts as well as early build-up and reliability growth testing of critical components as deemed necessary. Specific supplier controls or test methods, which indicate how defects are forced out and R growth is achieved, shall be identified.

- Contractors shall document their efforts for all items identified as critical, and shall code those items considered flight safety critical. Contractors' efforts shall describe procedures, tests, test results, growth status and efforts to reduce the degree of criticality of each item.

- Documentation for critical items shall be submitted initially prior to PDR and updated quarterly.

Figure 3-17

CRITICAL ITEM CONTROL CRITERIA

- Contractors' plans shall show approaches and methods by which he intends to control subcontracted material including the imposition of requirements on subcontractors in accordance with MIL-STD-785 and 470.

- Subcontractor programs shall include:

  - analytical tasks such as apportionment, prediction, FMECA, FRACA and performed with the same degree of rigor as contractor efforts.

  - a component control and standardization effort which interrelates with contractor's control program (especially in the areas of commonality of critical component approval, maximum stress criteria and qualification rationale).

  - growth tests, demonstration tests and qualification tests on subcontracted items.

- Subcontractor's documentation shall include an R&M program plan, a schedule for accomplishing R&M tasks and a list of deliverable documentation.

- Submittals of subcontractor data and reports shall be timed to fit logically into contractor's development schedule.

Figure 3-18

SUBCONTRACTOR R&M CONTROL CRITERIA

- Reviews shall be performed against a comprehensive checklist and criteria for R&M and provide the means for formal Army assessment of contractor design effort.

- Review procedures shall provide for formal reviews (with Army participation) as well as informal reviews conducted internally.

- Formal reviews shall include PDR, CDR, R&M, Program Managers and Mock-up reviews. Specific checklists shall be prepared for each review and shall cover the items shown in Figure 3-20.

- Review procedures shall contain methods for deficiency follow-up control.

- A detailed checklist and agenda shall be submitted prior to formal review--prior to PDR and CDR.

Figure 3-19

DESIGN REVIEW CRITERIA

Preliminary Design Review

- Identification of critical components
- Program plans
- Preliminary test plans
- Design progress
- R&M allocations and predictions
- Maintenance concept
- Special studies (e.g., detailed tradeoffs, etc.)

Critical Design Review

- Subsystem and component specifications
- Test plans and procedures
- Critical component evaluations
- Final design configuration
- Safety features
- R&M analyses
- Test results

R&M Design Review

- R&M allocations
- R&M predictions
- FMECA
- Failure data
- Growth Test data
- Production R Assurance

Mock-Up Review

- Airframe/Drive System
- Engine
- Flight Controls
- Fuel system

Program Managers Review

- Supplier control
- Configuration management
- Cost/Schedule
- Documentation and Reports
- Status of overall project

Figure 3-20

DESIGN REVIEW CHECKLIST CONSIDERATIONS

- Contractor's development test plan for reliability growth testing shall show a vigorous test, fix, retest program which emphasizes comprehensive and detailed failure analysis activity, show relationships between various time factors, growth rates and starting/end points.

- Specific growth test plans shall be formulated as part of the integrated test program and shall show:

  - predicted MTBF,
  - demonstrated MTBF,
  - starting point,
  - growth rate.

- Growth plans shall include the cumulative test time required to grow to the specified MTBF, the number of test units subjected to growth tests and the anticipated test time per unit. In addition:

  - Contractor's growth plans shall indicate realistic time factors which recognize that, in order to grow under a constant level of corrective action, sufficient downtime must be allowed for adequate implementation of corrective action before restarting the growth tests.
  - plans shall include:

    calendar time/month available,
    test time/calendar time,
    description of test cycle (environment on/off time).

- Growth test plan shall be submitted as part of overall integrated test plan at CDR.

- Progress of growth testing shall be tracked, and logs and data forms maintained that record number of units on test, test time accumulated, failures, corrective actions and level of reliability of MTBF achieved during time period.

- Final growth test report shall be submitted within 30 days after completion of test.

Figure 3-21

RELIABILITY GROWTH TESTS CRITERIA

- Contractor test plan shall indicate test to be conducted per MIL-STD-781B (e.g., Fig. 1, Test Plan III, level F with $\alpha = \beta = 10\%$, and $\theta_0/\theta_1 = 2/1$)
- Plan shall indicate reliability level (i.e., MTBF) to be demonstrated and the associated confidence level, and shall show the relationship between demonstrated MTBF, confidence, test time, etc.
- Plans shall show number of units for test, expected test time, calendar time factors, and scheduling of effort.
- Contractor's plan shall indicate the kinds of data to be gathered during the test and relationship to M tests.
- Contractor shall submit the R demonstration plan as part of the integrated test plan at CDR.
- Program of demonstration testing shall be tracked and logs/data forms maintained that record number of units on test, test time accumulated, failures, corrective action, statistical decision factors and accept/reject criteria.
- Monthly summary reports shall be submitted, and a final report shall be prepared per MIL-STD-781 and submitted within 30 days after completion of test.

Figure 3-22

RELIABILITY DEMONSTRATION TEST CRITERIA

- Contractor test plans shall indicate test to be conducted per MIL-STD-471 (e.g., Method 4 where repair time distribution is unknown, number of trials $\geq$ 50 and confidence levels at 75 & 90%). Plan should include:
  - parameters to be demonstrated,
  - confidence associated with demonstration (i.e., relationship of the number of failure events (trials) to the total potential failure modes from FM & EA studies),
  - number of units (or systems) involved,
  - repair levels.
- Government R&M task force representatives shall be involved in the selection of simulated maintenance trials (failures) to be induced into the system.
- M demonstration plan shall specify scheduling of M demonstration effort and duration of effort, and shall indicate data to be recorded during test.
- Plan shall be submitted as part of the integrated test plan in time for CDR.
- Progress of demonstration testing shall be tracked and logs/data forms maintained which record number of trials, nature of repair, repair time, statistical decision factors and criteria for success.
- Summary reports shall be prepared which indicate the test status. A final report shall be prepared within 30 days after completion of test.

Figure 3-23

MAINTAINABILITY DEMONSTRATION TEST CRITERIA

- Contractor's plans shall describe methods for reporting, analysis and corrective action of all failures regardless of their apparent magnitude through a formal "closed loop" failure analysis function.

- Plan shall indicate that activities are to be controlled by a formal written procedure which describes methods, personnel responsibilities, forms, documentation submittals and scheduling of effort. Plans shall indicate specific failure recurrence control procedures and include the following:

  - basic failure analysis approach,
  - failure analysis procedures,
  - depth of analysis
  - forms and reporting formats,
  - corrective action follow-up procedures.

- Contractor's plans shall indicate the applicability of FRACA activities with regard to all development, qualification, pre-qualification, acceptance, growth, demonstration, critical item and other test activities, and their extension through design, development and production of the aviation system. Plans shall contain sufficient detail to describe the sequence of events which occur upon detection of a failure including methods for failure verification and classification.

- Failure analysis methods shall be described which indicate the physical analysis techniques and controlled testing efforts currently used to determine the causes of failure.

- Plans shall describe corrective measures based on physics of failure techniques to eliminate (or minimize) the failure mechanism. These measures involve (as applicable):

  - component selection criteria,
  - special non-destructive tests to weed out specific failure mechanisms,
  - qualification requirements,
  - special in-process fabrication inspections and tests,
  - component stress/strength criteria,
  - special reliability assurance provisions.

Figure 3-24

FAILURE REPORTING, ANALYSIS AND CORRECTIVE ACTION CRITERIA

- Data collection effort shall provide management information suitable for long range planning for future Army needs and shall include experience information in the following categories:

  - resource requirements,
  - logistics requirements,
  - training requirements,
  - overhaul programs,
  - system improvement,

  and provide the basis for accurate field assessments of R&M.

- Plan shall provide specific mechanisms for collecting operational, maintenance and installation data at field sites, depots, disposal areas and during factory test for feedback to the Army data base.

- Data collection shall consist of detailed procedures, document forms and responsibilities for implementation and shall utilize, where practicable, existing procedures, forms and methods of collection.

Figure 3-25

R&M DATA COLLECTION CRITERIA

- Contractor's plans shall indicate methods by which he assures that the inherent reliability designed into equipment is not degraded during production. Plans shall describe methods for incoming inspection, in-process and final (acceptance) testing. Plans shall show effort in the areas of test, fabrication and inspection procedures and methods of handling/storing components, subassemblies and other production items.
- A statistically derived quality control plan shall be implemented and designed to achieve maximum control at minimum cost, and which includes increased and more comprehensive inspection at all levels of assembly.
- Plans shall show methods by which forced-defect test concepts are applied and which incorporate stress/screening at lower levels of assembly.
- Reliability shall be continually assessed during production through detailed analysis of production process flow, actual reject rate statistics and estimates of inspection efficiency factors.
- Scheduling shall show production reliability procedures to be prepared during design with initial submittal at CDR and updated as required prior to full scale production. Summary reports indicating current production reliability shall be submitted continually during full scale production.

Figure 3-26

PRODUCTION RELIABILITY ASSURANCE CRITERIA

- Contractor's plans shall indicate his effort to determine the actual achieved reliability based on system testing (qualification) or actual field use.
- Assessments shall indicate the relationship between predicted R&M values and achieved R&M values.
- Assessments shall be performed during validation, development, production, deployment and disposal phases. Bayesian statistics could be used to combine the results of theoretical considerations, engineering analysis and test results to yield R&M assessments which utilize the widest possible range of available data and information.
- Plan shall show sources of data, data reduction effort and the feedback of these results to Army via an assessment report.
- Assessments should include all pertinent data, such as analytical results (e.g., predictions), development test data (e.g., R growth), demonstrations, production and field test data.

Figure 3-27

R&M ASSESSMENT CRITERIA

- The organization for R&M shall consist of an identifiable group, separate from design, QC, etc., whose manager has direct access to program management and who reports at the same level as design.
- The R&M organization shall be defined with respect to its own critical R&M functions as well as with respect to allied functions (e.g., QC, manufacturing, etc.).
- The names of key people shall be listed.
- The R&M organization shall consist of a team of specialists which include expertise covering all R&M areas (e.g., statistics, physics of failure, component engineering, etc.).
- The R&M manager shall possess sign-off authority on design efforts with respect to R&M.
- The overall guiding philosophy of the R&M program shall be defined and the impact on the design effort established (e.g., define fully the tie in with early design results and describe the interaction of all R&M tasks).
- A schedule shall be provided showing all tasks as well as the interaction of each task with other R&M tasks and task timeliness relative to design and other efforts. Programs and hardware milestones shall identify applicable R&M constraints.
- A list of deliverable items and delivery dates shall be provided (see Figure 3-29).
- Contractor's program plans shall state his intended methods of control (e.g., meetings, PERT, reviews, audits, etc.), and include discussions of policy formulation and information dissemination and status reporting.
- Plans shall indicate R/D status reporting including format, scheduling and delivery.

Figure 3-28

R&M ORGANIZATION & CONTROL CRITERIA

TASK	SCHEDULE	TASK	SCHEDULE
1) Reliability Apportionment			
• report	Shortly after award of development contract (prior to PDR)	11) System Growth Tests	
		• plan/procedure	Part of integrated test design and planning activities. To be submitted at CDR.
2) Reliability Prediction and Analysis		• interim test data	Include in Program Status Report (monthly)
• report	At PDR & CDR	• final test report	Within 30 days after completion of test.
3) Failure Mode Analysis		12) Reliability Demonstration Test	
• report	At PDR & CDR		
4) Maintenance Concept		• plan/procedure	Part of integrated test design and planning activities.
• plan	At PDR	• interim test data	To be submitted at CDR-include in Program Status report (monthly).
5) Maintainability Allocation		• final test report	Within 30 days after completion of test.
• report	Shortly after award of development contract (prior to PDR)	13) Maintainability Demonstration Test	
6) Maintainability Prediction		• plan/procedure	Part of integrated test design and planning activities. To be submitted at CDR
• report	At PDR & CDR		
7) Component Control and Standardization		• test report	Within 30 days after completion of test.
• plan	At PDR	14) Failure Reporting, Analysis and Corrective Action	
• maximum stress criteria	At PDR		
• component specifications	As needed and consistent with procurement schedule	• procedure	Initial at PDR - final at CDR
• vendor controls		• failure reports	Timely submittal immediately after occurrence of failure - possible one-to-one correspondence after achievement of R maturity.
8) Critical Item Control		• failure analyses	
• list	Prior to PDR (update quarterly)	• corrective action	
9) Subcontractor R&M Control		• failure summaries	Part of monthly status report
• R&M Program Plan	Full description in system contractor's program plan	15) R&M Data Collection	No documentation requirement other than full description in R&M Program Plan.
• Schedule of deliverable items	At PDR	16) Production Reliability Assurance	
• Data and reports	As required to fit into system contractor's schedule	• plan/procedure	Part of integrated test design and planning activities. To be submitted at CDR
10) Design Reviews			
• agenda	15 days prior to each review (PDR & CDR)	17) R&M Assessments	
• checklist		• report	As required
• deficiency follow-up	As required	18) Overall R&M Organization and Control	
		• R&M Prog. Plan	Shortly after award of development contract (prior to PDR)
		• R/D Status Reports	Monthly

Figure 3-29

RECOMMENDED R&M DOCUMENTATION COMPLETION/SUBMITTAL SCHEDULE DURING DEVELOPMENT AND PRODUCTION

with respect to R&M, but will also establish the course for subsequent R&M management activities during development and production.

This proposal evaluation can be performed by utilizing the 18 review points, and their associated criteria, given in the previous section. These criteria are representative of a well-rounded R&M program applicable to a high reliability, full-military-development type of program (Option 3B, Level 1). The information provided by contractors' proposals relative to each of the 18 R&M review points provides the data base for evaluation. Contractor proposals for other development options and levels would be evaluated relative to a reduced list of review points or on the basis of restricted task criteria.

Factors that must be incorporated into the evaluation criteria are:

(1) Compliance with Requirements

(a) Proposals must show compliance with the values of the R&M parameters defined in the RFP documents.

(b) Proposals must comply with the intent of applicable specifications and data requirements.

(c) Proposed values of R&M must be capable of demonstration without minimizing performance capability or incurring excessive cost.

(2) Understanding of the Problem

(a) Proposals must demonstrate contractors' understanding of the scope or range of tasks which make up the R&M effort.

(b) Proposals must show an understanding of R&M technology: mathematical/statistical modeling, hardware engineering (stress factors), physics of failure, etc.

(c) Proposals must show a knowledge of advanced, yet proven methods for R&M programs.

(d) Proposals must show an understanding of the interaction between various R&M elements and the system design and development process, including the interface aspects of R&M with development milestones.

(3) Soundness of Approach

(a) Proposals must indicate that the manpower, facilities and other resources are adequate to implement the approach described.

(b) Proposals must show that the approach to R&M possesses sufficient flexibility to accommodate design changes, program delays, or extension of R&M elements.

(c) Proposals must indicate that the contractor can meet the objectives of the R&M program within the scheduled time period.

(d) Proposals should contain any suggested extensions or exceptions beneficial to the Government.

(4) Technical Expertise

(a) Proposals must contain sufficient background or prior experience in R&M and related areas to convince AVSCOM of their capability.

(5) Management

(a) Proposals must show how the contractor's R&M management structure for the proposed program functions within the overall corporate and program management. This includes personnel assigned, their technical expertise, management techniques, and lines of communication.

In order to evaluate contractor proposals quantitatively, methods of assigning weight factors to each review point can be devised.

One such method of scoring relative to an Option 3B, Level 1, R&M program (shown by the previous 18 review points) uses a scale of 100 points. The scale of 100 is subdivided relative to each review point's contribution and importance to effective functioning of the overall R&M program. This subdivision is shown in Figure 3-30. Other scales and subdivisions based on a reduced list of review points can be derived readily.

	REVIEW POINT	WEIGHT FACTOR
1	Reliability Apportionment	5
2	Reliability Prediction and Analysis	10
3	Failure Mode Analysis	5
4	Maintenance Concept	5
5	Maintainability Allocation	2
6	Maintainability Prediction and Analysis	4
7	Component Control and Standardization	5
8	Critical Item Control	5
9	Subcontractor R&M Control	5
10	Design Reviews	5
11	System Growth Tests	10
12	Reliability Demonstration Test	8
13	Maintainability Demonstration Test	5
14	Failure Reporting, Analysis and Corrective Action	5
15	R&M Data Collection	3
16	Production Reliability Assurance	5
17	R&M Assessments	3
18	Overall R&M Organization and Control	10
		100

Figure 3-30

WEIGHT FACTORS FOR EVALUATING CONTRACTOR R&M PROGRAMS

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SECTION 4.0

THEORY AND APPLICATION OF R&M

4.1 General

4.2 Foundations for Application of R&M Theory

- 4.2.1 Reliability
- 4.2.2 Maintainability

4.3 R&M Techniques, Procedures and Guidelines

- 4.3.1 Basic Modeling Concepts
  - 4.3.1.1 R&M Modeling
  - 4.3.1.2 Concepts of Availability
- 4.3.2 R Prediction, Allocation and Assessment
  - 4.3.2.1 MIL-HDBK-217 R Prediction Techniques
  - 4.3.2.2 Part and Component R Prediction Techniques (Probabilistic Design)
  - 4.3.2.3 R Allocation Technique
  - 4.3.2.4 R Assessment Using Bayesian Statistics
- 4.3.3 M Prediction, Allocation and Assessment
  - 4.3.3.1 M Prediction (MIL-HDBK-472)
  - 4.3.3.2 M Prediction (New Concepts)
- 4.3.4 Other R&M Evaluation Techniques
  - 4.3.4.1 Failure Mode Analysis
  - 4.3.4.2 Reliability Growth Testing
  - 4.3.4.3 Production and Operations and Maintenance (O&M) Control
  - 4.3.4.4 Nondestructive Testing and Evaluation
- 4.3.5 Maintainability Demonstration
- 4.3.6 Failure Analysis

4.4 R&M Improvement

Section 4.0
THEORY AND APPLICATION OF R & M

4.1 General

In order to implement the provisions and guidelines outlined in Section 3.0 of this guide, methodologies and techniques must be available for use by both contractors and Army management and engineering specialists. This section describes some of the more essential techniques available for application to a well controlled R&M program. As an introduction, fundamentals of reliability theory are discussed with specific guidance suggested for application of the theory to complex mechanical systems and components. In practice, many of the techniques discussed in this section would be implemented by AVSCOM contractors. During the critical development and production phase, reliability evaluation models prepared by the contractors and monitored by the Army (Figure 4-1) provide a key tool to predict, track and assess reliability. All contractor-Army personnel responsible for reliability should be fully aware of the latest evaluation techniques available to the practitioner. This section will not attempt to present an exhaustive review of reliability methodology but only cover the more important, recently developed techniques, that are not fully documented in standard reliability texts. Special emphasis is given to techniques that have specific application to Army aviation systems and components.

4.2 Foundations for Application of R & M Theory

4.2.1 Reliability (Reference 4-1)

The exponential formula for reliability introduced in Section 1.0 can be derived from the basic definition of probability. Furthermore, it will be shown that based on probability rules, a general reliability formula can be derived regardless of whether the failure rate is constant or variable. The implication of the derivation is that regardless of the type of

Contractor	R & M Division Product Assurance Directorate-AVSCOM	Project Manager's Office
Create, exercise, and update R & M model using latest failure rate data. a. Identify required functions for each phase of each required mission and define what constitutes a failure. b. Identify critical time periods and equipment in the exercise of each function. c. Identify the external stresses under which the system must function. d. Analyze, and quantitatively include in the model, the planned and defined operational and maintenance concepts. e. Submit periodic outputs of model.	Monitor contractor activities to verify model inputs and assure operation of models as contractually required. Assess contractor performance and make recommendations to cognizant project manager concerning validity, credibility, accuracy, etc. of math model and its outputs. Coordinate with interfacing Commands as required.	Provide overall guidance and control. Evaluations from supporting activities, primarily product and directorate. Give approval of contractors product based on recommendations from supporting activities.

Figure 4-1 EVALUATION MODELS-CONTRACTOR/GOVERNMENT

failures that characterize the component being considered, fundamental reliability theory can be validly applied.

When a fixed number, N_o, of components are repeatedly tested, there will be, after a time t, N_s components which survive the test and N_f components which fail. The reliability or probability of survival is at any time t during the test:

$$\boxed{R(t) = \frac{N_s}{N_o} = N_s/(N_s + N_f)}$$

Since $N_s = N_o - N_f$; reliability can be written:

$$\boxed{R(t) = \frac{N_o - N_f}{N_o} = 1 - \frac{N_f}{N_o}}$$

and

$$\boxed{\frac{dR}{dt} = \frac{-1}{N_o} \frac{dN_f}{dt} = f(t)_i}$$

where

$f(t)_i$ = the failure density function, i.e., the probability that a failure will occur in the next time increment dt.

Let:

$z(t)_i$ = The hazard rate, or the probability that a failure will occur in the next instant of time assuming previous survival, then:

$$z(t)_i = \frac{-f(t)_i}{R(t)_i}$$

The quantity $z(t)_i$ can be defined as the hazard rate of element i at time t. In general, it can be assumed that the hazard rate of electronic elements and complex mechanical systems remain constant over practical intervals of time, and that $z(t)_i = \lambda_i$ = the constant, expected number of random

failures per unit of operating time of the ith element, i.e., the failure rate. Thus, when a constant failure rate can be assumed:

$$\boxed{z(t)_i = \lambda_i = \frac{f(t)_i}{R(t)_i} = -\frac{\frac{dR(t)_i}{dt}}{R(t)_i}}$$

Solving this differential equation for $R(t)_i$ gives the exponential distribution function commonly used in reliability prediction:

$$\boxed{R(t) = \epsilon^{-\lambda_i t}}$$

Also, the mean time to failure can be determined by:

$$\boxed{MTBF = \int_0^\infty R(t)\,dt,}$$

so that, when a constant failure rate λ_i can be assumed:

$$\boxed{MTBF_i = \int_0^\infty \epsilon^{-\lambda_i t}\,dt = \frac{1}{\lambda_i}}$$

The above expression for $R(t)_i$ and $MTBF_i$ are the basic mathematical relationships used in reliability prediction. It must be noted, however, that these expressions were derived based on the fundamental assumption that the failure rate of the item under consideration is a constant. When the failure rate is not constant, the more general hazard rate must be considered, in which case the element reliability is obtained using the more general expression:

$$\boxed{R(t)_i = \epsilon^{-\int_0^\infty z(t)_i\,dt}}$$

The emphasis on the exponential distribution in reliability work makes a discussion of the use of this function as a failure-probability model worthwhile. The mechanism underlying the exponential reliability function is that the hazard rate (or the conditional probability of failure in an interval, given survival at the beginning of the interval) is independent of the accumulated life.

The use of this type of "failure law" for complex mechanical systems is usually justified because of the many forces that can act upon the system and produce failure. For example, different deterioration mechanisms, different part hazard-rate functions, and varying environmental conditions often result in effectively random system failures.

Another justification for assuming the exponential distribution in long-life complex systems is the so-called "approach to a stable state," wherein the system hazard rate is effectively constant regardless of the failure pattern of individual parts. This state results from the mixing of part ages when failed elements in the system are replaced or repaired. Over a period of time, the system hazard rate oscillates, but this cyclic movement diminishes in time and approaches a stable state with a constant hazard rate.

A third justification for assuming the exponential distribution is that the exponential can be used as an approximation of some other function over a particular interval of time for which the true hazard rate is essentially constant. For example:

(1) quality defects--represent early failures and have a decreasing hazard rate.

(2) reliability (or stress related) defects--represent failures during the early and useful life period; have a constant (or slightly decreasing) hazard rate.

(3) wearout defects--represent failures during the normal and end-of-life period; have an increasing hazard rate.

(4) engineering (or design) defects--normally represent early failures and have a decreasing hazard rate; however, an immature design can allow these defects to dominate all other defects.

These four components of failure are shown pictorially in Figure 4-2.

As previously indicated, the basic assumption normally made in reliability or MTBF prediction is that, during the useful life period, the sum of the above components would result in a constant hazard or failure rate that can be described by the exponential failure distribution. This means that:

> The hardware item must reflect a mature design where design failures have been eliminated or minimized, quality defects have been minimized, wearout is not noticeable or is beyond the period of concern.

It should be noted that for aviation components and parts, the sum of the three above failure characteristics will not necessarily result in a constant failure rate. This is because aviation systems are primarily comprised of mechanical components and parts. Failure analysis studies indicate that while electrical parts normally exhibit a long useful life period with a relatively high constant or random failure rate, mechanical parts are characterized by a short useful life period with a relatively low random failure rate. Both part categories exhibit similar early failure characteristics. Thus, in general, wearout failure is the dominant characteristic with respect to mechanical parts and random failure is the dominant characteristic with respect to electrical parts. In order for the exponential distribution to be valid for helicopter systems, systematic and deliberate reliability

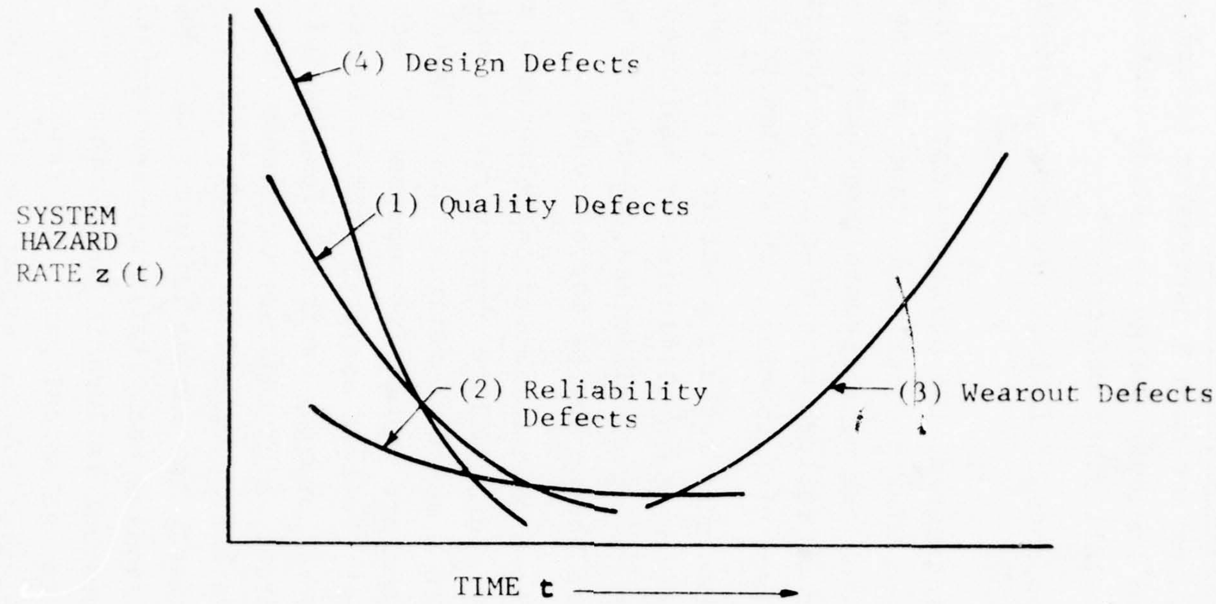


Figure 4-2

SYSTEM FAILURE COMPONENTS

program provisions as described in Section 3.0 must be applied during development.

Effort must be directed to:

1. Design mechanical components to extend their life and to minimize the effects of wear;
2. Minimize quality and manufacturing defects through the application of production reliability assurance program; and
3. Minimize design failures through design reviews and application of R&M checklists and similar control provisions.

4.2.2 Maintainability

Maintainability is defined as the probability that a hardware item will be retained in or restored to a specified operating condition within allowable time limits using available test equipment, facilities, personnel, and spare parts, and will be performed in accordance with prescribed procedures. Maintainability prediction is the process of estimating the parameters that describe this probability and as reliability prediction, is an analytical process. Maintainability is based on design characteristics and maintenance features (i.e., test points, self check features, accessibility, modularization, adjustments, etc.) to determine the ease and speed with which maintenance operations can be performed and failures can be diagnosed and corrected.

In general, maintainability is composed of two parts:

(1) Corrective maintenance - the action performed, as a result of failures, to restore an item to a specified condition, and
(2) Preventive maintenance - the action performed in an attempt to retain an item in a specified condition by providing systematic inspection, detection and prevention of incipient failure.

As failures are quantitatively assessable in terms of reliability as a function of time, repair may be quantitatively evaluated in terms of times required to perform elementary

maintenance activities. These time elements may be mathematically combined to form statistically meaningful measures of system downtimes through several conventional techniques described in the following discussion.

Factors that are most commonly used by the military are:

- Mean Downtime (MDT)
- Mean Time Between Maintenance (MTBM)
- Mean Time To Repair (MTTR)

Maintainability, as expressed by these factors, is driven by reliability, as described in the previous section.

MDT incorporates all time elements involved in performing the maintenance activity and includes mean maintenance time, mean waiting time, mean logistics time and mean administrative time.

MTBM mathematically combines mean time between unscheduled maintenance action with mean time between scheduled maintenance actions and may be expressed as follows.

$$MTBM = \frac{1}{1/MTBM_u + 1/MTBM_s}$$

where

$MTBM_u$ = Mean time between unscheduled maintenance action

$MTBM_s$ = Mean time between scheduled maintenance action

MTTR is defined in terms of failure rate data $\left(\lambda = \frac{1}{MTBF}\right)$ obtained from reliability studies and maintenance time factors derived from a review of system or component design characteristics.

Conceptually, the repair of hardware items after the occurence of a failure necessitates the initiation of a corrective maintenance task which ultimately results in the interchange of a replaceable part or assembly. In order to achieve

a complete "repair", various activities both before and after the actual interchange are necessary. These activities can be subdivided into the following time elements.

<u>LOCALIZATION TIME</u> -- The objective of localization is to eliminate as many as possible of the unfailed functions from further consideration by performing rapid tests (frequently involving only operating controls, displays and/or monitoring devices) before proceeding with the more difficult diagnostic techniques of fault isolation.

<u>ISOLATION TIME</u> -- The time associated with tracing a failure down to a replaceable item through the use of test equipment.

<u>DISASSEMBLY TIME</u> -- That time associated with gaining access to the replaceable part, up to the point of interchange.

<u>INTERCHANGE TIME</u> -- The time associated with the physical removal of a failed item and its replacement with a new item.

<u>REASSEMBLY TIME</u> -- The time associated with disassembly, except that the steps are performed in reverse order.

<u>ALIGNMENT TIME</u> -- The time associated with the manipulation of operating and maintenance controls and mechanical parts so as to bring the equipment within its specified operating ranges.

<u>CHECKOUT TIME</u> -- The time associated with the verification that the repair has restored the equipment's normal performance.

The composite time for all the above activities is called the repair time, R_p. In order to provide weight factors for the expected number of corrective maintenance actions, the failure rate of each replaceable component/part/assembly is used. The failure rate and repair time are combined to arrive at a corrective maintenance action rate. This process is repeated for each replaceable component/assembly in the system. From the maintenance actions rates (R_p) derived for each replaceable item, the MTTR can be determined using the following expression.

$$\text{MTTR} = \frac{\sum (R_p)(\lambda_p)}{\sum \lambda_p}$$

4.3 R & M Techniques Procedures and Guidelines

Mathematical evaluation models are used to apportion R&M requirements to various elements of hardware within the total sytem, and to further predict the design's inherent reliability and maintainability levels. Estimates based on evaluation models then become benchmarks for subsequent R&M assessment efforts.

Other reliability efforts are concerned with trading and measuring the growth of reliability during the development effort, and with assuring that reliability is not degraded during production or during operation and maintenance of the helicopter. Maintainability prediction techniques are concerned with diagnostic techniques and maintenance schemes, and with assurance that acceptable maintainability is achieved during use.

Although several methods and techniques are employed during the development effort to evaluate R&M, they all rely on prediction techniques to provide quantitative measures.

Reliability and maintainability evaluation techniques can be classified into the categories shown in Figure 4-3.

4.3.1 Basic Modeling Concepts

4.3.1.1 Reliability and Maintainability Modeling

In order to evaluate the reliability of systems and equipment, a method is needed to reflect the reliability connectivity of the many part types having different stress determined failure rates that would normally make up a complex equipment.

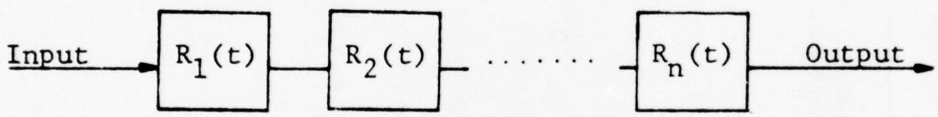
	Allocation	Prediction	Assessment	Assurance Techniques	Other Evaluation Techniques
Reliability	• Series Models • AGREE • Weighting Models	• MIL-HDBK-217A(B) • Probabilistic Design	• Bayesian Techniques	• Production • Operating & Maintenance	• FMEA • Reliability Growth Tests • System Reviews • Failure Analysis
Maintainability	• Tradeoff Studies • Previous Experience • Equal Availability	• MIL-HDBK-472 • Mean Time to Remove & Replace Based on FIT	• Logistics • Diagnostics • Repair Level • Design Review	• Task Selection • MIL-STD-471 • Demonstration Tests • Non-destructive Tests	• ORLA • Maintenance Degradation Analysis • Maintenance Concept Tradeoffs • Time Study Analysis

Figure 4-3

CLASSIFICATION OF R&M EVALUATION METHODS AND TECHNIQUES

This is accomplished by establishing a relationship between equipment reliability and individual part/item failure rates. This relation, known as the system reliability mathematical model, can be established for the basic equipment configurations. For most equipments or systems, equipment failure is a reflection of part failure. Or, stated more precisely, it is assumed that the equipment fails when any individual part fails. This is known as a serial reliability configuration. Failure of any one part in the series would result in failure of the equipment. Further, it may be assumed that failure of any part would occur independently of the operation of other components.

The equipment configuration may be represented by the following block diagram:



Reliability of the series configuration is the product of the reliabilities of the individual blocks:

$$R_s(t) = R_1(t) \cdot R_2(t) \dots R_i(t) \dots R_n(t)$$

where

$R_s(t)$ is the series reliability, and $R_i(t)$ is the reliability of the "i^{th}" block for the time "t".

Figure 4-4 is a partial list of the helicopter equipment hierarchy. The life cycle phases of a helicopter development program are also listed. The figure suggests that as the program progresses from conceptual to detailed design, hardware is defined at a lower level of the assembly. Reliability prediction, allocation and assessment is required during all development program phases while the techniques required to predict reliability should be continually updated

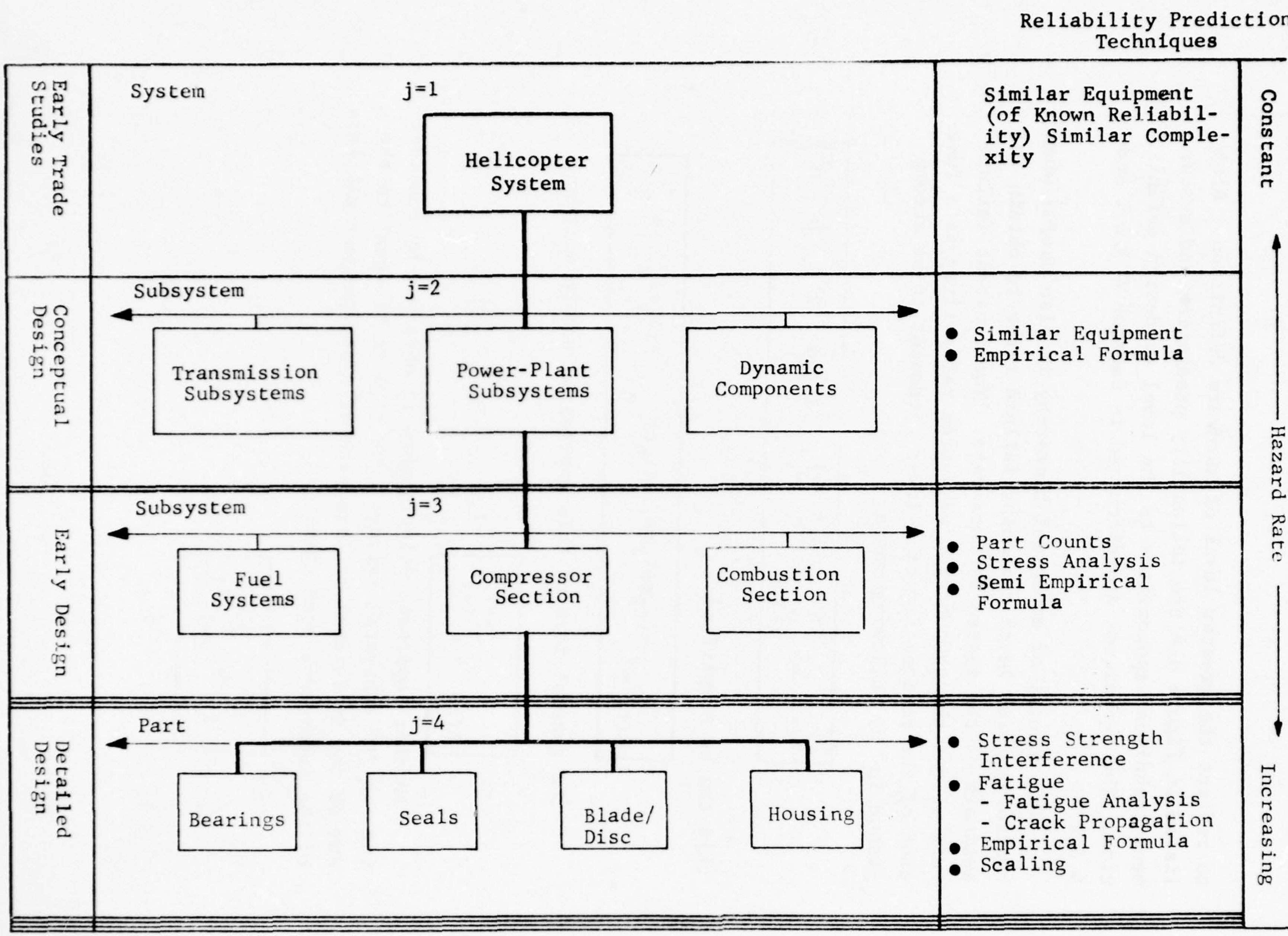


Figure 4-4

HELICOPTER EQUIPMENT HIERARCHY (Partial Listing)

to reflect the greater level of hardware definition. Also listed in Figure 4-4 are reliability prediction and assessment techniques appropriate to the level of design definition. The techniques are discussed in Section 4.3.2.1 and 4.3.2.2.

The concept of equipment hierarchy is also useful when combining lower level component failure rates to obtain an estimate of the system failure rate. The constant failure rate allows the computation of system reliability as a function of the reliability of a lower component to be accomplished in the following manner:

$$\boxed{R(t) = \prod_{i=1}^{n} \epsilon^{-\lambda_i t} = \left(\epsilon^{-\lambda_1 t}\right) \cdot \left(\epsilon^{-\lambda_2 t}\right) \ldots \left(\epsilon^{-\lambda_n t}\right)}$$

This can be simplified:

$$\boxed{R(t) = \epsilon^{-(\lambda_1 t + \lambda_2 t + \ldots + \lambda_n t)} = \epsilon^{-(\lambda_1 + \lambda_2 \ldots + \lambda_n) t}}$$

The general form of this expression can be written:

$$\boxed{R(t) = \epsilon^{-t \sum_{i=1}^{n} \lambda_i}}$$

Another important relationship is obtained by considering the jth subsystem failure rate (λ_j) to be equal to the sum of the individual failure rate of n independent elements of the subsystems such that:

$$\boxed{\lambda_j = \sum_{i=1}^{n} \lambda_i .}$$

Revising the MTBF formulas to refer to the system rather than an individual element gives the mean time between failures of the system as:

$$\boxed{\mathrm{MTBF} = \frac{1}{\lambda_j} = \frac{1}{\sum_{i=1}^{n} \lambda_i}}$$

Successive estimates of the ith subsystem failure rate can be made by combining lower level failure rates using

$$\boxed{\lambda_j = \sum_{i=1}^{n} \lambda_{ij} \quad (j = 1, \ldots m)}$$

where

λ_{ij} = the failure rate of the ith component in the jth level subsystem.

λ_j = failure rate of jth level subsystem.

As the equipment is defined to a greater level of detail, simple elements (parts) are designed, and it becomes increasingly difficult to justify the constant failure rate assumption for the reliability analysis. According to the reliability foundations discussion (Section 4.2), non-constant part hazard rates of many parts and components will combine and a constant failure rate can be considered a valid approximation for the higher level assembly:

$$\boxed{z_j(t) = \lambda_j = z_{1,j}(t) + z_{2,j}(t) + \ldots + z_{n,j}(t)}$$

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$$\boxed{z_j(t) = \lambda_j = z_{1,j}(t) + z_{2,j}(t) + \ldots. + z_{n,j}(t)}$$

where:

$z_{i,j}(t)$, $i = 1,2\ldots n$ are the non-constant hazard rates associated with part failure modes at time t, and

λ_j = the higher assembly level where the constant failure rate is valid.

For the non-constant hazard rate assumption it is recommended that further detailed reliability analysis at the part (failure mode) level employ probability theory to compute higher level equipment reliability. The equation can be written:

$$\boxed{R_j = \epsilon^{-\lambda_j t} = \prod_i^n (Ps_i) \cdot (1-P_j)}$$

where

$Ps_i = \epsilon^{-\int_0^\infty z(t)}$ dt, the probability of surviving the ith failure mode.

P_j = probability of failure due to failure mode interaction.

For equipment that has survived infant mortality Ps can be estimated using probabilistic design techniques that account for wear and cumulative damage effects. The last term in the above equation (P_j) may or may not be significant depending on the class of equipment being analyzed. The reason the term is included is that the inter-dependencies of failure modes could lead to a reliability that is less than the product of the individual survival probabilities. For example, a part has a probability of surviving the effects of corrosion or fatigue over the useful life, but still may have an additional probability of failure due to effects of both corrosion and fatigue acting together.

The constant failure rate (random failure) assumption is valid when making reliability predictions of major helicopter subsystems (e.g., power plant, transmission, avionics, etc.) during early trade and conceptual design studies and, in many cases, during early design evaluation. The random failure assumption is generally valid when a large number of failure mechanisms contribute to the failure of a component. Standard MIL-HDBK-217 A(B) prediction techniques, assuming a constant failure rate, will provide sufficient accuracy. During the detailed design phase, parts and components are designed and design and reliability analyses conducted. Cumulative damage theory, wear and fatigue theory all assume an end-of-life characteristic for the part, and usually an increasing hazard rate better approximates the actual reliability characteristics. Mechanical reliability prediction techniques (stress-strength-interference and probabilistic fatigue analysis) have been developed to estimate part failure probability and, hence, reliability. These techniques are probabilistic extensions of standard mechanical design analysis techniques and provide a great deal of insight into factors that lead to unreliability. Incorporating probabilistic design techniques into the reliability prediction methodology, using the approach suggested in the preceding discussion, would lead to early problem identification and correction.

Both a high level of analytical competence and sufficient time are required to implement a probabilistic (reliability) design analysis program. Fortunately, many mechanical components are overdesigned and can be eliminated without extensive analysis, while other part failures do not contribute to helicopter failure. A failure modes & effects analysis would help identify critical components for more extensive probabilistic design analysis. Components whose failure can cause a safety hazard require the highest level of attention and, therefore, should be subjected to the most rigorous and thorough design analysis.

It should be noted that components capable of causing safety hazards are but a fraction of the total helicopter component count. The various categories of reliability are illustrated in block diagram form in Figure 4-5. The reliability requirement and level of analytical and test effort are dependent on the criticality of the component failure. The expense of a probabilistic design analysis program, to identify and correct inherent design reliability problems early, would be compensated by the more costly hardware redesign programs that could potentially be eliminated.

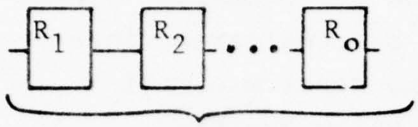
Maintainability models are developed in a similar fashion as that described for reliability. The evaluation of maintainability requires measurement of the factors which would tend to delay or speed up any action effecting a repair. The maintainability model must account for these factors. The most direct approach to developing the model is one which focuses on an accuracte appraisal of system downtime. Basically, system downtime can be broken into two categories, preventive maintenance downtime, and corrective maintenance downtime.

Preventive maintenance downtime is that time during which a system is shut down so that maintenance can be performed in order to prevent any anticipated failures. However, a preventive maintenance action does not always contribute to system downtime. Many tasks, such as adjustments, lubrications, and light cleanings, do not require a system shutdown. Thus, when considering preventive maintenance downtime, estimates must be made as to the fraction of time which will require an actual system shutdown.

Many factors enter into the estimation of preventive maintenance downtime; such as number of men and skill level. For simplicity, availability of a repairman often is not considered due to the assumption that a preventive maintenance task is being carried out by a repairman who can handle all portions of the task, and when the repairman causes a failure, he is immediately available to repair that failure.

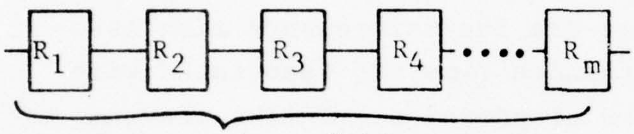
SERIAL CONFIGURATION

PROBABILITY OF SUCCESS (i.e., Reliability)



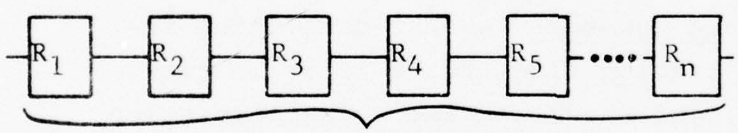
Components whose failure can cause a safety hazard

$R_{safety} = .999952$



Components whose failure can cause a safety hazard or a mission abort

$R_{mission} = .987$



Components whose failure can cause a Safety hazard, mission abort or an unscheduled maintenance action

$R_{system} = .778$

Figure 4-5

RELIABILITY BLOCK DIAGRAMS FOR SAFETY, MISSION ABORT AND UNSCHEDULED MAINTENANCE ACTIONS.

The number of men performing maintenance is obviously a factor in that increases in manpower will almost always reduce the amount of time required to effect a repair. Likewise, the skill level of the repairman also needs to be considered since it is usually the case that an above average repairman will need less time per maintenance task, and a below average repairman more.

Preventive maintenance downtime may be allocated into subintervals based on consideration of the number of men and their skill level. These subintervals are the maintenance time associated with replacements, maintenance time not associated with replacements based on pre-cursor diagnostics. Unlike preventive maintenance, corrective maintenance downtime consists exclusively of system downtime, the notable exception being parallel or redundant systems which are not considered in this discussion.

Corrective maintenance downtime is that time which includes increments of preparation time, fault location time, fix time, alignment time, and checkout time. The allocation of quantities to each of these increments is strongly influenced by design factors such as modularity, accessability, interchangeability and particularly, the degree of built-in test and fault isolation capabilities. These design factors must be carefully assessed when estimating downtime.

Corrective maintenance downtime must also take into consideration the skill level and number of personnel. However, estimates of corrective maintenance downtime must also consider a factor to account for the availability of a repairman, since it is highly unlikely to have a repairman present and available to service every random failure. Repairman availability is dependent on the facility's maintenance philosophy. The maintenance philosophy establishes the location of the maintenance pool relative to the item to be serviced and consequently, determines the repairman's travel time.

Just as the facilities maintenance philosophy was considered, so must the spare support philosophy. Major delays can be caused by difficulty in obtaining a spare, whether they are on-site, in depot, or in the worst case, if they must be procured out of depot.

The purpose of evaluating downtime in such a rigorous manner is to provide insights as to where problem areas exist in the determination of maintainability. Once this is accomplished, efforts can be directed to improve trouble spots and reduce MTTR.

4.3.1.2 Concepts of Availability

In determining the most effective system in terms of R&M, it is helpful to consider the concept of "system availability." This is a term which describes the percentage of time that a system will be capable of performing its intended function. It is defined mathematically as:

$$A = \frac{\text{total system uptime}}{\text{total system uptime + total system downtime}}$$

Total system uptime can also be expressed in terms of MTBF, and downtime in terms of MTTR. Availability becomes:

$$A = \frac{MTBF}{MTBF + MTTR}$$

Since there are several other definitions of availability, it is helpful to clarify the distinction between them at this point. The basic difference between them lies in the definition of MTTR. Intrinsic availability defines MTTR as consisting only of the actual active repair time and neglects any other logistic or personnel factors. On the other hand, Operational or System Availability defines MTTR to include the following times.

- Active Repair Time
  - Localization Time
  - Isolation Time
  - Disassembly Time
  - Interchange Time
  - Reassembly Time
  - Alignment Time
  - Checkout Time
- Waiting or Administrative Time
  - Administrative Time (paperwork)
  - Shipping Time
- Logistics Time
  - Maintenance Schedule Delays
  - Supply Methods

Figure 4-6 helps to clarify the distinction between Intrinsic and Operational Availability, by showing their operational cycles and the delay times considered in each. From the figure it can be seen that System Availability takes into consideration all delay factors and hence provides a realistic picture of the actual time the system will perform its intended function. Due to difficulty in evaluating total downtime, care must be exercised in assessing System Availability due to the large number of factors that will effect its actual value.

From the preceding discussion it can be seen that System Availability provides a useful tool in determining how anticipated improvements in reliability or maintainability will affect the actual time the system can be used, at any phase in its operational life. Therefore, application of the availability concept and related models during design provides a basis to perform tradeoffs and sensitivity analyses and to force the design to be iterated to optimize R&M. Application of availability analysis during development and production facilitates improvement and growth of service availability to assure the

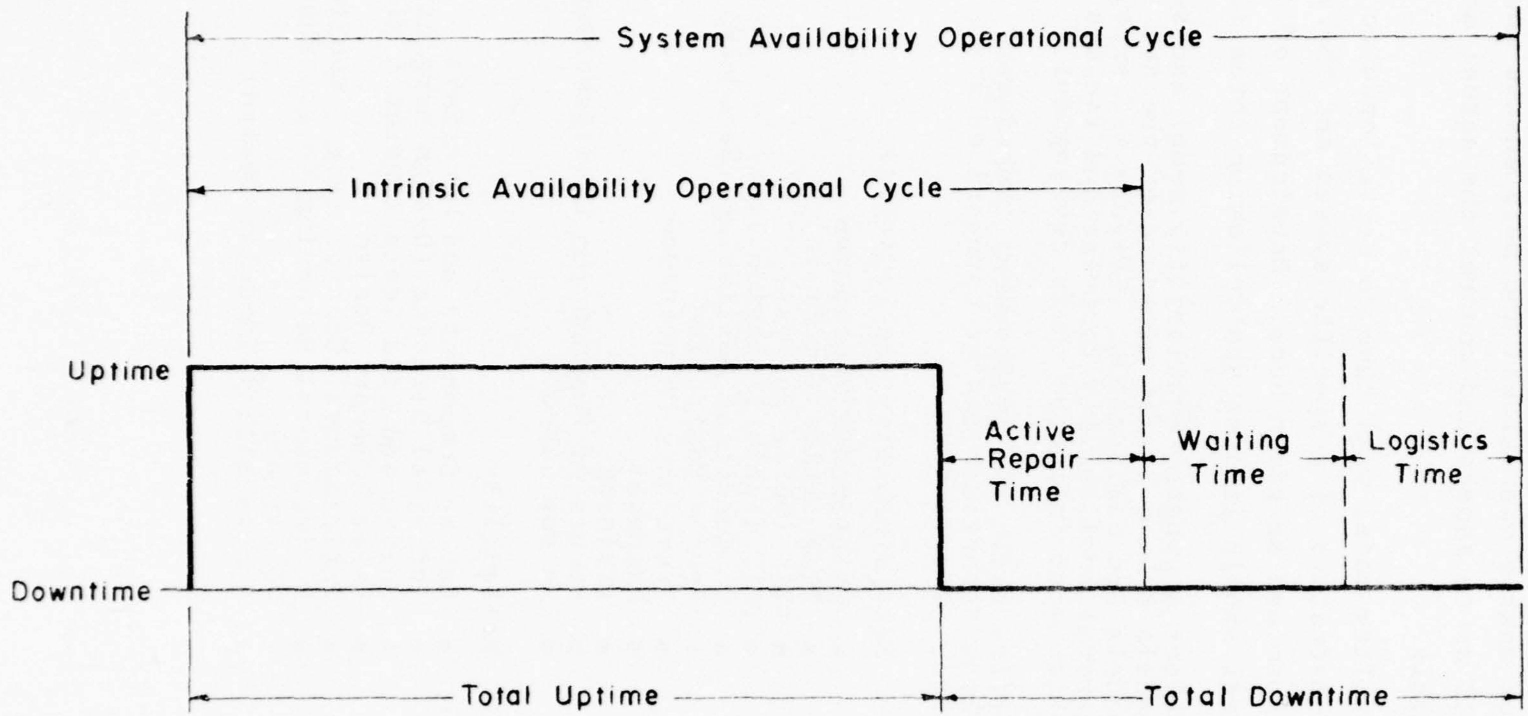


Fig 4-6 OPERATIONAL CYCLES FOR INTRINSIC AND SYSTEM AVAILABILITY

achievement of the optimum level. Application of the availability concept during field use provides a systematic and consistent basis for making operational and maintenance management decisions as well as to assess and control the actual achieved availability levels.

Any availability model will have to be tailored to meet the needs and constraints of a specific system and therefore only a general form can be given here. Development of an availability model should include the following three steps:

<u>Step 1</u> - Select a general availability model and submodels from a review of state-of-the-art models and users needs. (Figure 4-7 provides general availability formulae and factors which will influence their development.)

<u>Step 2</u> - Define basic R&M improvement techniques. These techniques can be categorized into three major areas:

(1) Maintainability and Logistics

- Maintenance Procedures
- Diagnostics (Built-In)
- BIT (Built-In Test)
- FIT (Fault Isolation Test)
- On Condition Monitoring (Secondary Effects)
- Remote Monitoring
- Preventive Maintenance
- Manpower
- Training
- Levels of Support (On Line/Base/Depot)
- Spares Support

(2) Reliability

- Better Components and Materials
- Increased Derating (Design Margins)
- Screen and Load Tests (Design & Mfg.)
- Fault Tolerant Design
- Environmental Control (e.g., Cooling)
- Environmental Hardening (e.g., Shock, Vibration)
- Accessibility (Modular Design)

Inherent Availability

$$A = \frac{MTBF}{MTBF + MTTR}$$

$$MTBF = 1/\lambda$$

$$MTTR = \bar{M}_{CT} = \frac{\sum_{1}^{N} M_{CTi}}{N}$$

where: M_{CTi} = time to perform corrective maintenance action i

N = number of corrective maintenance actions

Factors determing Inherent Availability

1) Reliability (λ)
2) Mean Active Corrective Maintenance Time

Operational Availability

$$A_o = \frac{MTBM + \text{readytime}}{(MTBM + \text{readytime}) + MDT}$$

$$MTBM = \frac{1}{1/MTBM_U + 1/MTBM_S}$$

MDT = (mean maintenance time) + mean waiting time) + (mean logistics time) + (mean administrative time)

Ready time = Operational cycle - (MTBM + MDT)

MTBM = Mean time between all maintenance action

$MTBM_U$ = Meantime between unscheduled maintenance action

$MTBM_S$ = Meantime between scheduled maintenance action

MDT - Mean Downtime

Factors determining Operational Availability

1) Frequency of maintenance
2) Active maintenance
3) Waiting time
4) Logistic time
5) Administrative time
6) Ready time

Figure 4-7 AVAILABILITY FORMULAE AND DETERMINING FACTORS

(3) R&M Program Provisions

- Incentive Contracts
- Warranty Provisions
- R&M Test Provisions
- R&M Control Provisions
- R&M Growth Testing
- Critical Parts Control
- FMECA (Failure Modes and Effects Criticality Analysis)
- Vendor Control Program

<u>Step 3</u> - Modifies the general availability model, as necessary, to include factors that take directly into account the R&M improvement techniques.

Once the availability model has been formulated, it should be applied to the system to improve availability. R&M improvements shall be identified independent of each other, with the use of the model in each case. This scheme allows evaluation of the relative merit of each "improvement." Such a comparison allows a judgment to be made of where to concentrate improvement efforts to most effectively approach availability goals. This technique is illustrated in Figure 4-8 and shows the overall availability improvement which may be attained. Specific factors for improving availablity through improvements in reliability and through improvements in ease of maintenance are discussed further in detail in Section 4.4.

4.3.2 Reliability Prediction, Allocation, and Assessment

The reliability techniques discussed in this section can be, and in some cases have been, applied to complex mechanical systems. Their implementation in any specific helicopter program would depend on the level of reliability required, scheduling factors and cost constraints (recommended reliability analysis levels of effort were included in Section 3.3).

Reliability allocation, or apportionment, is closely related to reliability prediction. A prediction of system reliability is obtained by determining the reliability of the lowest level items and proceeding through intermediate levels until an estimate of system reliability is obtained. Reliability allocation begins

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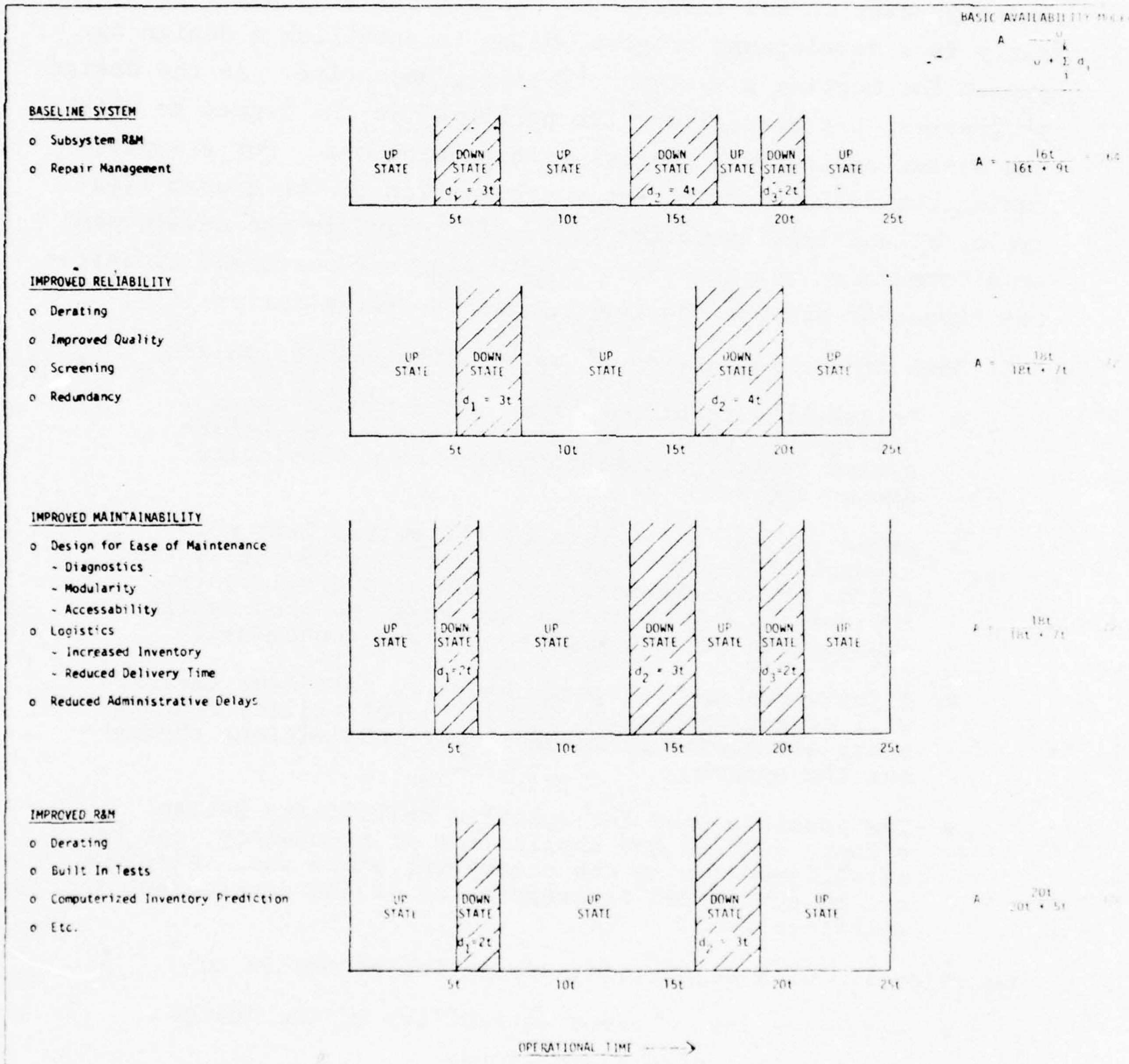


Figure 4-8

AVAILABILITY IMPROVEMENT

with a statement of the overall system reliability requirement and apportions this total requirement among subsystems and lower subdivisions constituting the system.

In actual application there is considerable overlap between prediction and allocation. An allocation usually performed early in a development program, helps to establish a design approach for meeting a system reliability objective. As the design progresses, the predictions are performed to the degree to which the system reliability objectives are being met. For example, during the definition and early acquisition of the system life-cycle, allocations are often performed to and in the development of alternate approaches while predictions are performed to assess the impact of proposed design changes on system reliability.

Some of the advantages of reliability allocation are:

- Reliability requirements are apportioned among the various parts and units of the system before system design becomes committed to a particular design approach.
- Attention can be focused on the reliability relationship between various subdivisions of the system, and on the contribution of each to overall system reliability, early in the design stage when design changes can be made more easily and economically.
- A judicious apportionment based on pertinent factors will result in placing realistic reliability requirements among subsystems and lower subdivisions throughout the system.
- The possible need for specific reliability design effort, such as the application of redundancy, can be established during the conceptual phase and, therefore, can be considered in preparation of the development's specification.

The objective of a reliability prediction effort is to:

- establish the inherent reliability of the design,
- aid design tradeoff decisions,
- provide criteria for R growth testing,
- identify and help eliminate design failures,
- provide quantitative input for early support provisioning planning,
- support cost of ownership & acquisition cost studies, and

provide a visible direct method to compare with the reliability requirements.

A underlying objective of a reliability prediction effort is to introduce reliability discipline into the design effort. To predict reliability, a design analyst is required to evaluate each part and component, and for each failure mode, to consider the design safety margin, and the stress, load, and material strength factors. Inherent defects can, therefore, be diagnosed at an early phase in the design process when corrective action can be made on paper--not on production hardware.

Both MIL-HDBK-217 A(B) reliability prediction techniques and probabilistic design procedures incorporate stress/strength concepts and derating factors when evaluating the reliability of a design. The MIL-HDBK and probabilistic approaches are sufficiently different, and merit separate discussion.

4.3.2.1 MIL-HDBK-217 Reliability Prediction Techniques

The basic concept which underlies the calculation of reliability numerics, as presented here, is that system failure is a reflection of part failure. Consequently, individual part failure rates are applicable within a series reliability model such that the system failure rate can be calculated by the sum of individual part failure rates.

Similarly, part failure rate prediction models have been developed (primarily by the military) based on large scale data collection and analysis activities, failure mode and physics of failure studies. These models, in general, incorporate basic stress dependent generic part failure rate data which are modified by suitable adjustment factors derived specifically for the item under study. The basic modal failure rates, data and adjustment functions are derived from established sources.

These models vary with part types however, their general form is:

$$\boxed{\lambda_{part} = (\lambda_b)(K_1)(K_2)}$$

where:

λ_{part} is the total part failure rate.

λ_b is the base failure rate. The value is obtained from reduced part test data for each generic part category, where the data is generally presented in the form of failure rate versus normalized stress and temperature curves. The part's primary load stress factor and its factor of safety is reflected in this basic failure rate value.

K_1 is the design adjustment factor. This factor depends upon inherent part properties (e.g., complexity, gross power ratings, configuration) arising from the selection of a particular part design.

K_2 is the use adjustment factor. This factor depends upon the assembly application of the part, and takes into account secondary stress factors and application factors that are considered reliability significant.

A part's operating environment consists of two major stress types: load and thermal. Stress conditions take into account the part's strength compared to its applied (or operating) stress. The stress ratio is regarded as normalized operating stress with respect to part strength at a reference temperature, usually 25°C ambient. Rated strength data is compiled from part drawings and other design information. Operating stress data is evaluated through a stress analysis

and other design and stress information, in conjunction with actual measurements.

These factors represent the kinds of data required to perform a part-by-part MTBF analysis. The implementation of these concepts is illustrated in Appendix C.

<u>Similar Equipment Techniques (Base Failure Rate Data)</u>

Army helicopter contractors maintain a data base consisting of past helicopter failure information. The failure data is accumulated in the subsystems and part level and is collected through the military data reporting system (TAMMS/TAERS, 3M, 66-1 and special R&M contractual data gathering efforts). Internal data reporting of test information, or data from commerical helicopter experience, is often included in the file. The data base is quite large and includes a variety of helicopter types and classes operating in a full spectrum of environmental conditions. Section 2.0 of this guide presents failure data for the OH-58, CH-47 and other helicopters. The broad spectrum of helicopters presently in the field virtually insures that failure rate data is available on a comparable system.

Care is required when using a data base that relies on maintenance information. As indicated in Section 2.0, the data often includes operator and maintenance errors, scavenging and environmental damage. It is inappropriate to include failures caused by the above factors when estimating a design's inherent reliability.

<u>Semi-Empirical Subsystem R Prediction Techniques</u>

Application of empirical techniques is limited to equipment in a mature state of development. Future helicopters may be required to carry larger payloads and have larger diameter rotors. Engines will develop higher shaft horse-power and higher turbine temperatures. A higher horsepower-to-weight

ratio will probably be a future development objective. Performance improvements generally increase stresses and loads which the designer compensates for by increasing the strength of the components. For the existing materials technology and design environment, trends could be expected between MTBF and helicopter performance parameters.

Empirical (MTBF) data on fielded helicopter components subsystems form the basis for formulas that allow interpolation and prediction of reliability for developmental helicopter subsystems and components. The formulas can be as simple as a single performance parameter related to MTBF or a non-linear regression model consisting of several key helicopter performance variables. For example:

MTBF (air frame) = f(Wt, SHP, etc.)

MTBF (engine) = f(SHP, op. hrs., combustion chamber temp., fuel type, etc.)

or MTBF (rotor blade & hub) = f(rotor diam., payload, hp, environment, etc.)

Once the corrolation coefficients are determined, the formulas could be interpolated to determine the MTBF of developmental helicopter characteristics. Extrapolation of the formula to allow prediction of MTBF would yield valid results if the new design incorporated design features and materials similar to those of the fielded helicopters.

Part Count Techniques

Part count reliability prediction techniques are useful during early design when enough information is available to estimate the part count of the design. When the prediction is made at the system level, and the class of equipment is comprised of a very large number of parts, MTBF should generally be a function of the complexity (part count) of the helicopter. The part count prediction technique is a commonly

used tool for electronics systems. A typical part count versus MTBF curve is shown in Figure 4-9.

Fielded helicopter data can be utilized to construct similar curves for the helicopter. Care must be taken when defining an active element (part) in the system. Load carrying rivets, O Rings, and seals should be counted, non load carrying rivets should not.

4.3.2.2 Part and Component R Prediction Techniques (probabilistic Design)

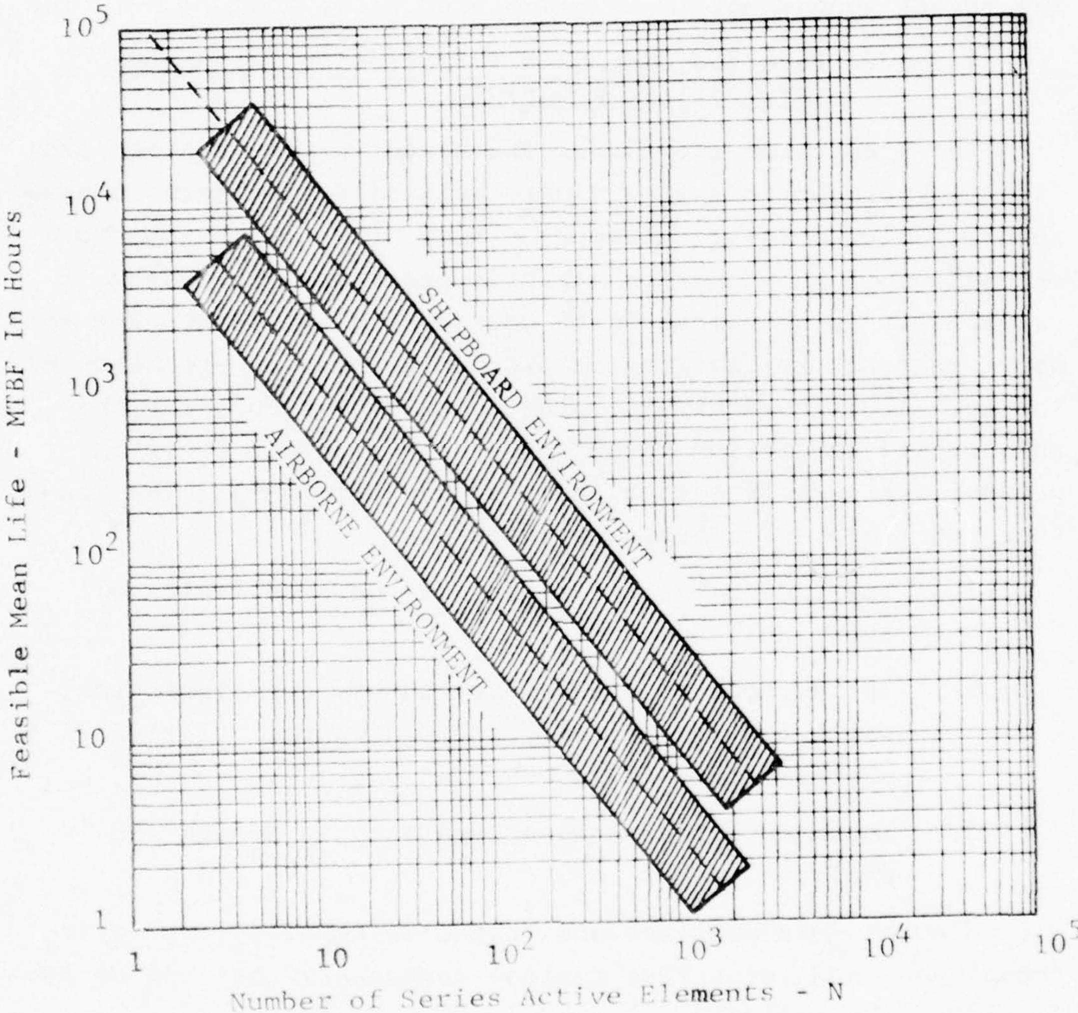
The prediction techniques discussed in this section provide an approach to estimate part reliability subject to non-random failures (e.g., wearout). Many of the techniques are extensions of known design analysis procedures but assume variability is associated with each design estimate. For the above reasons, reliability prediction becomes an extension of the normal design analysis. The underlying theory for the reliability prediction technique can be found in texts on probabilistic designs (for example, see Ref. 4-2). The reasons for the probabilistic approach are:

1. The random variations in the characteristics of individual compnents.
2. The methods of probability theory and statistics, which provide a means of defining the relative possibilities of such variations.
3. The need for a rational approach in design and analysis.

Figure 4-10 summarizes analytical reliability prediction techniques, and identifies typical components that can be subjected to the analysis.

Stress--Strength Analysis (Safety Factor & Interference)

The basic idea behind stress/strength and reliability theory is that a given part has certain physical strength



(Reproduced From MIL-STD-756A)

Figure 4-9
MTBF VERSUS FUNCTIONAL COMPLEXITY

ANALYTICAL TECHNIQUES		SIGNIFICANT VARIABLES	TYPICAL ELEMENTS & EQUIPMENTS
Fatigue Design	High Cycle Fatigue Low Cycle Fatigue Thermal Fatigue	Main stress Alternating stress Stress frequency Stress concentration factors Endurance limit Yield & ultimate strength Load cycles	Blades Shafts Linkage Belts Gears
Stress/Strength Analysis	Safety Factor Interference	Significant stress (Failure theory) Significant strength (Material properties) Stress variation (error analysis) Strength scatter values	Housings Struts Frames Actuators Tubes & Vessels Flywheels
Empirical Design Formulas		Geometrical properties Physical properties Loading properties Environmental factors	Gears (wear) Splines Joints Fasteners Sliding bearings
Life Prediction Equations (Derating)		Rated life Usage factors Derating factors Material factors	Bearings (rolling contact) Springs Hose Cable
Failure Data (Scaling)		Failure rates Usage loads Speed Environmental factors	Seals Brakes Solenoids Filters Pumps

Figure 4-10

PART LEVEL RELIABILITY PREDICTION TECHNIQUES

properties which, if exceeded, will result in failure. Further, this property, as with all properties of nonhomogeneous material, varies from specimen to specimen. Thus, for a particular part or material an estimate of the mean value and of the dispersion of the strength property may be found by testing.

The operating stress imposed on a part also varies. These stresses vary from time to time in a particular part, from part to part in a particular design, and from environment to environment. As estimate of the mean value and the dispersion value of the operating stress must be determined by test, analysis or experiment.

Typical helicopter equipments elements that can be analyzed using stress/strength analysis include:

- Housings
- Struts
- Frames
- Actuators
- Tubes
- Flywheels

The typical engineer is trained to think in terms of a safety factor. The interference theory is discussed from this viewpoint, in terms of normal distributions. The use of normal distributions is justified since, in some cases, both the applied load and strength of a part may be presented with sufficient accuracy, for reliability prediction purposes, by the normal distribution curve. The application of stress stength theory is not limited to the normal distributions.

For the purposes of this discussion, the factor of safety (F.S.) can be represented by

$$\boxed{F.S. = \frac{\mu_T}{\mu_S}}$$

(see Figure 4-11)

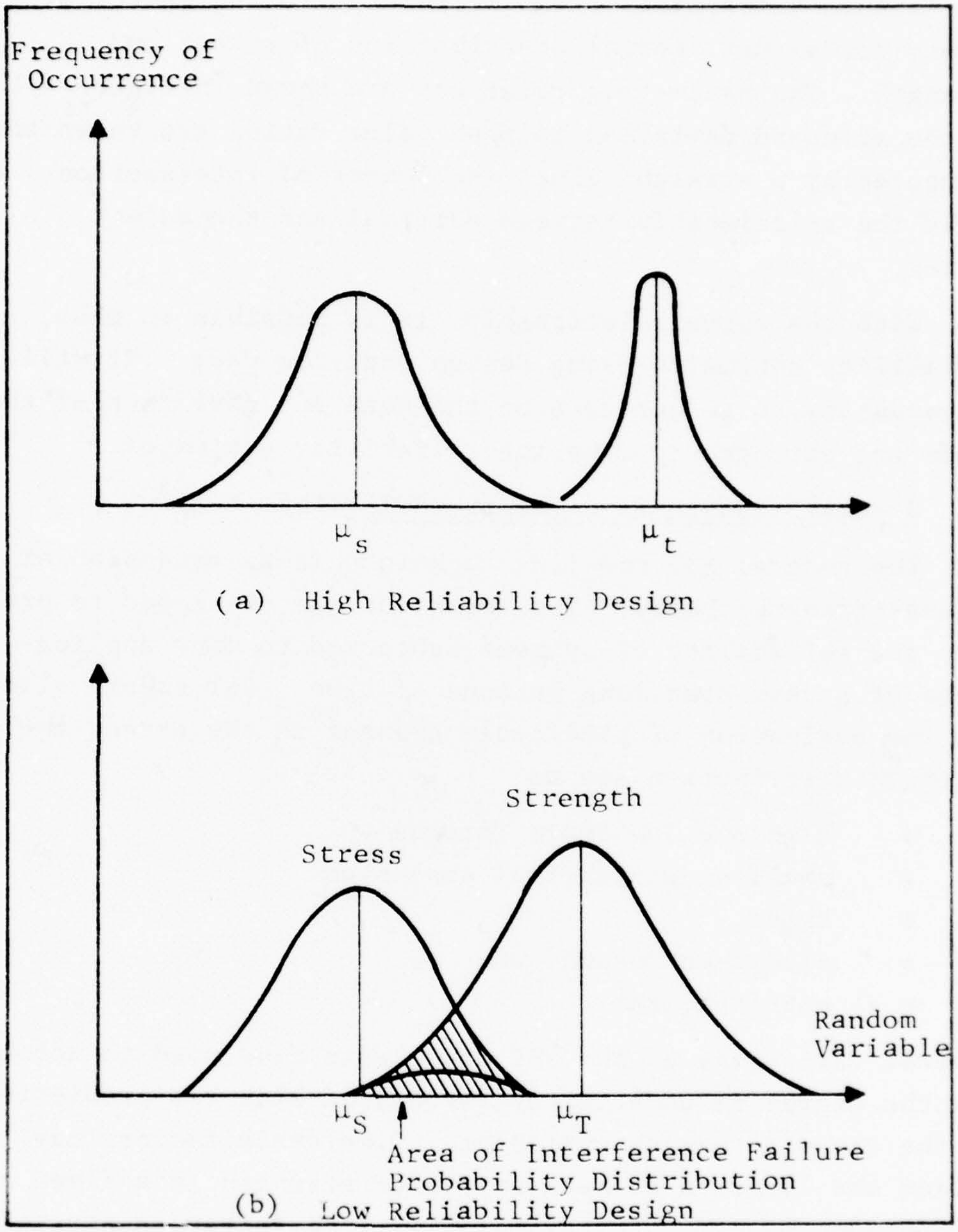


Figure 4-11

TYPICAL STRESS-STRENGTH INTERACTION DIAGRAM

The failure probability P can be related to the factor of safety for assumed normal distributions of stress and strength. The parametric relations are shown in Figure 4-12 If the standard deviation to mean value ratios are known and connected by a straight line, the points of intersection yield the relationship between survival and the safety factor.

With the above relationship, it is possible to make reliability estimates using design analysis data. It will be necessary to gather data on the mean and deviation of the loads and strength to make the reliability estimates.

Stress-Strength-Time Theory (SST) (Ref. 4-3)

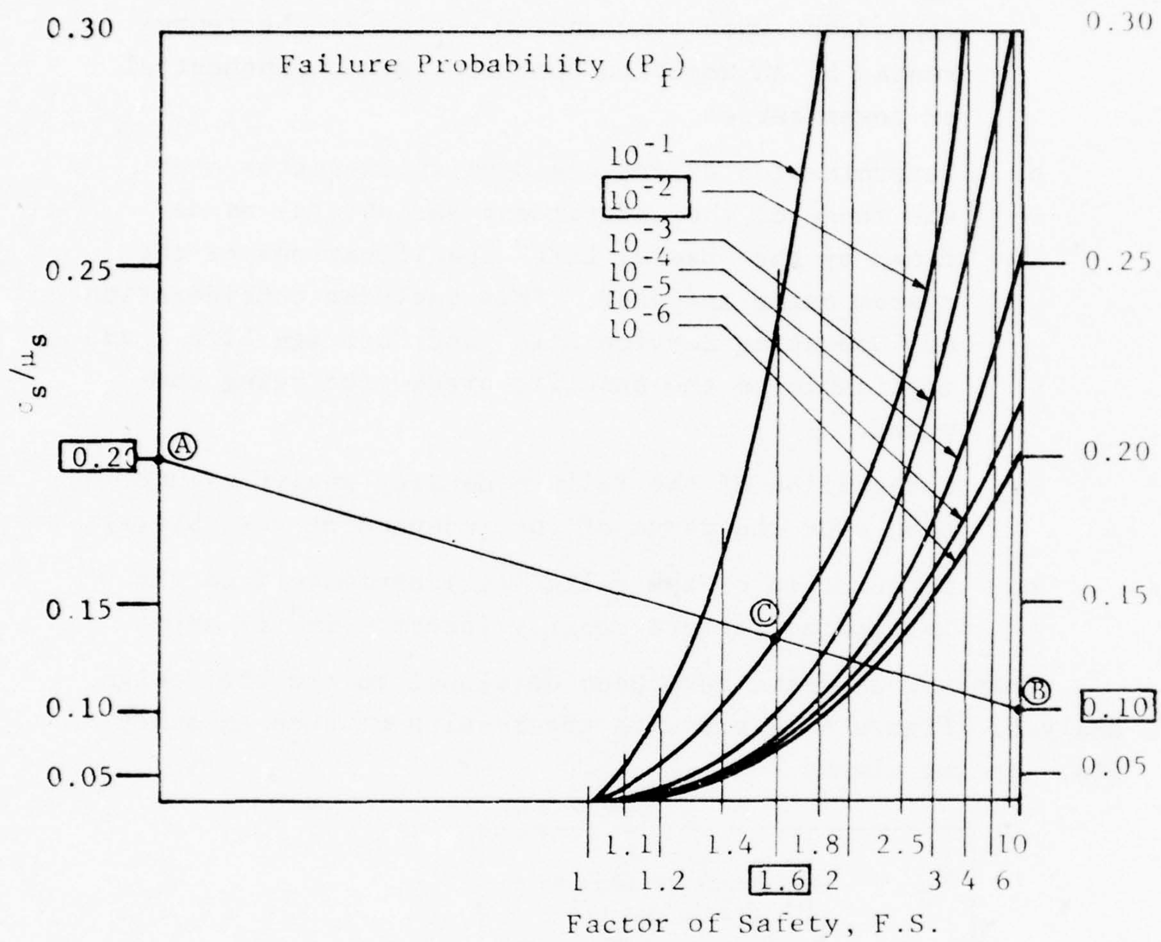
The general SST modeling technique is an extension of stress-strength theory. The technique was developed to predict the reliability of systems subjected to many applications of stress over long periods of time. SST theory allows for the evaluation of time/cycle changes in the stress and strength distribution due to

- high and low cycle fatigue
- swelling and thermal expansion
- creep
- stress corrosion, and
- embrittlement

Several variations of the SST model were developed to account for the degree of uncertainty associated with the prediction of the stress/strength variables. Time/cycle factors may effect the location of mean stress or strength in a fixed or independent manner. For example, if time factors constantly reduce strength (cumulative damage theory), an increasing failure rate can be expected.

Reliability modeling using the SST model required:

a. Estimates of "Stress/Strength" distributions at several values of the independent variables' time,



SAMPLE PROBLEM:

Given: σ_s is 20% of μ_s $\quad \frac{\sigma_s}{\mu_s} = .20$ (point A)

σ_t is 10% of μ_t $\quad \frac{\sigma_t}{\mu_t} = .10$ (point B)

Construct line from A to B
F.S. = 1.6 (intersects A-B at C)

Answer: $P_f = 10^{-2} = .01$ or $R = .99$

Figure 4-12

SAFETY FACTOR RELATED TO A PROBABILITY OF FAILURE

cycles or some combination of these such that their dependence upon time and/or cycles can be represented by an analytic function, e.g., exponential or power series.

b. Determination of failure density estimates over the range of the independent variable(s) as defined by the "Useful Life" specifications of the system being analyzed. This includes consideration of "Operating Service Life" and "Storage Life," as applicable to the specific prediction being computed.

c. Integration of the failure density analytic function over the range of the independent variable(s).

d. Computation of the reliability estimate from the integrated failure density function in (c) above.

Computer programs have been developed to aid the design analyst. Figure 4-13 presents the results of such an analysis. In the figure:

$$\boxed{K_D = \frac{\mu_T - \mu_S}{\sqrt{(\sigma s)^2 + (\sigma_T)^2}}}$$

K_D is related to the design safety factor previously described. Shown in the figure is the decrease in reliability as stress application (cycle or time) increases. A family of curves results from various assumptions concerning the certainty that the stress/strength parameters can be estimated.

Fatigue Design Analysis (The P-S-N Approach) (Ref. 4-4)

Applicable to:

Blades
Shafts
Links
Belts
Gears
Bonded Surfaces

SAMPLE PROBLEM:

Mean stress μ_s = 9000 psi

Standard deviation σ_s = .20 (μ_s) = 1800 psi

Mean strength μ_t = 25000

Standard deviation σ_t = .10 (μ_t) = 2500 psi

$$K_D = \frac{\mu_t - \mu_s}{\sqrt{\sigma_t^2 + \sigma_s^2}} = 5. \sim 4.95 \text{ (curve A)}$$

Average stress Applications Per Mission $\overline{N}$ = 5

Number of Missions $\overline{N}_m$ = 2000

Total Stress applications $N = \overline{N} \cdot N_m = 10000 = 10^4$ (point B)

R_{max} = .9997 (point C)

R_{min} = .992 (point D)

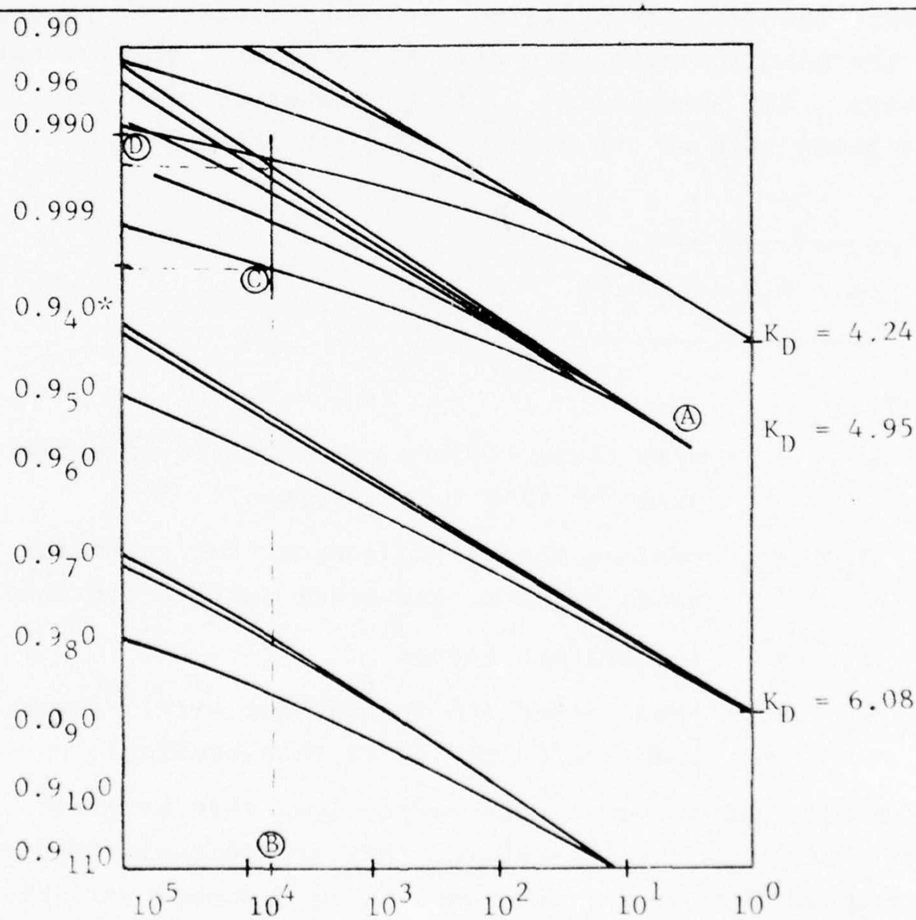


Figure 4-13
RELIABILITY ESTIMATE R_N OF FAILURE MODELS
CHARACTERIZED BY STRESS-STRENGTH INTERFERENCE METHOD

*The subscripted number refers to the number of 9's in the Reliability value.

Figure 4-14 is a typical S-N curve modified to account for cumulative damage theories which also includes confidence levels. Data is becoming available for a wider range of materials, making fatigue analysis a useful reliability prediction tool.

Deterioration due to corrosion is shown in Figure 4-15. Corrosion will modify the fatigue characteristic of the material.

In the calculation of fatigue strength, it is traditional to determine the S-N curve for a particular material under standard test conditions (completely reversed bending stress, room temperature, 0.3 inch specimen diameter, polished surface). The data are utilized for other conditions by adjusting the mean strength with several "standard" multiplicative factors. For example, if μ_T is the observed mean strength at a given life or the fatigue strength then:

$$\boxed{\mu_T' = K_1 K_2 K_3 K_4 \mu_T}$$

where

K_1 = size factor (where component is of different diameter than test specimen).

K_2 = surface factor (to account for corrosion, notch effects, and other surface finishes).

K_3 = temperature factor

K_4 = load factor (to account for axial, shear, or load conditions other than bending).

These multiplicative factors may be less than or greater than unity. In the literature, they are commonly treated as constants when, in fact, each K_i is a random variable.

SAMPLE PROBLEM:

S_i is the estimated alternating stress on the bonded surface between the closure and C spar on a helicopter rotor blade. Using conventional stress Analysis techniques (Goodman Diagram, S-N, curve A), the bonded surface should withstand an infinite number of cycles, when curve A is modified to account for stress risers, non-zero mean stress and the effects of cumulative damage; the mean life of the blade is N_m cycles. N_s cycles represent the Life of the blade where 10% failures are tolerated. Blade replacement should be scheduled before N_s cycles are accumulated. Note the P=10% curve is dependent on quality control of the manufacturing process and will definitely effect the life of the blade.

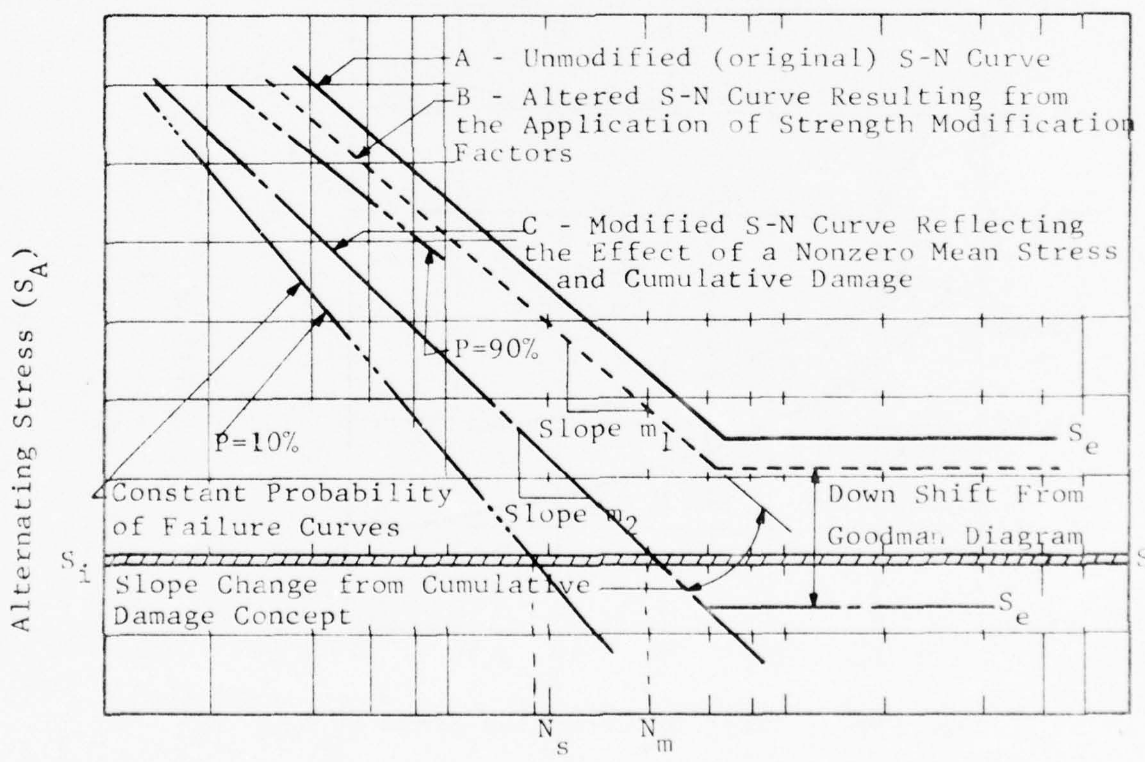


Figure 4-14

EFFECT OF MODIFYING FACTORS ON THE BASIC S-N CURVE

SAMPLE PROBLEM:

A significant failure mode for the "801" Tail Rotor Hub Assembly is retention failure at the threaded connection between the Tail Rotor Grip Assembly and Retention Nut. This failure mode results in the loss of the tail rotor blade in-flight. This is a safety critical failure mode.

Corrosion has been identified as a possible causal factor responsible for the failure mode. Corrosion is known to effect the fatigue strength characteristic of helicopter material. The fatigue strength of Nickel steel in air is 55000 psi, (point A in the figure). After 25 days corrosion alone reduces the fatigue strength of the steel 29% (point B) and under cyclic loading a 39% reduction in strength was observed (point C). The figure can be used to modify the Goodman Diagram (Figure 4.2.1.9) and reliability can be estimated using the P-S-N approach. Note the shape of Curves 1 and 2, implies the part will have an end-of-life characteristic.

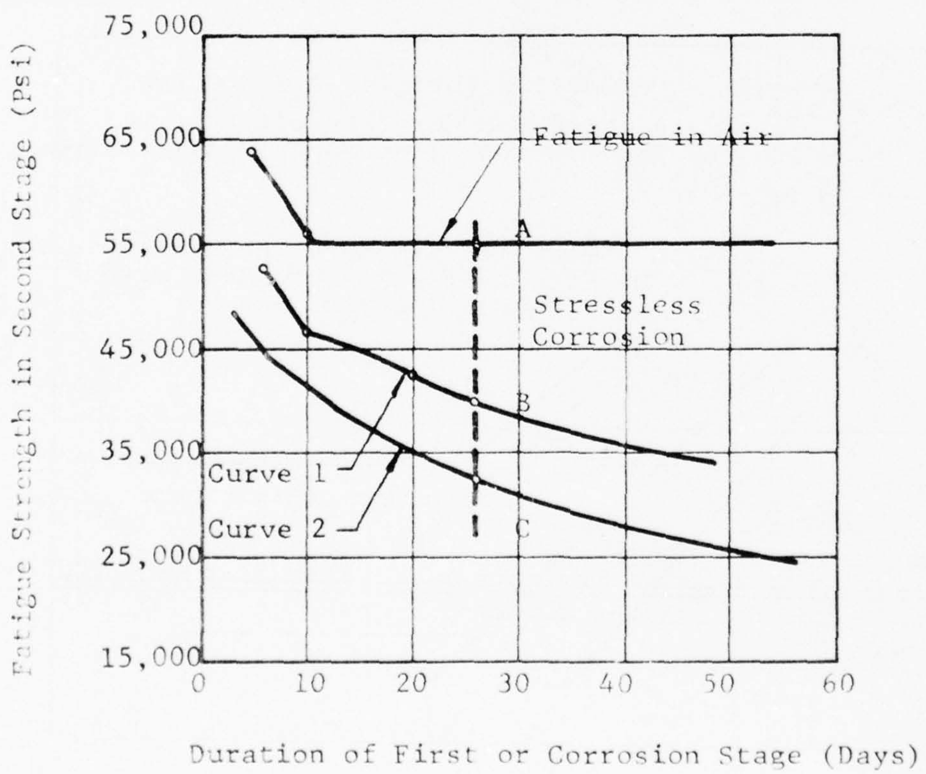


Figure 4-15

CORROSION FATIGUE TEST CURVES
FOR 3-1/2 PERCENT NICKEL STEEL

It is a random variable because repeated experiments to determine the value of this correction factor will create a sampling distribution of K_i.

The method assumes that:

1) Fatigue strength under "standard" conditions and under service conditions is normally distributed.

2) Each K_i is normally distributed.

3) Estimates of the mean and standard deviation of both fatigue strength under "standard" conditions, and of K_i are available.

The purpose of the method is to obtain a point estimate of reliability in service for mechanical components subjected to fatigue failure. The basic model for prediction of reliability is the interference model discussed previously. The particular problems which can be solved by the methods of the present section are the adjustment of strength distribution parameters obtained under "normal" test conditions to account for such factors as load, size, surface condition, temperature etc.

Fatigue and Crack Void Propagation Models (Ref. 4-5)

The crack propagation model illustrated in Figure 4-16 is an extension of fatigue theory, and is particularly applicable to structures and panels subject to fatigue loading. The statistical model for the fatigue process can be used to carry out a reliability analysis enabling the probability of failure to be estimated at any stage of the structure life. The statistical variability in crack propagation rate and residual strength of the cracked structure is included together with the effect of any prescribed inspection procedure.

SAMPLE PROBLEM:

Voids in bonded joints are known to provided stress risers that lead to crack initiation and propagation. Cyclic loads (Fatigue) will simultaneously cause the size of the crack to increase and the strength of the joint to decrease. Failure of the blade occurs at N_L where the mean load S_m exceeds the strength of the cracked surface. At life N_s variability in crack length and strength allows us to estimate reliability using interference theory (see Figure 4-12). Methods of increasing blade life could include inspection for voids or the use of techniques to limit crack growth.

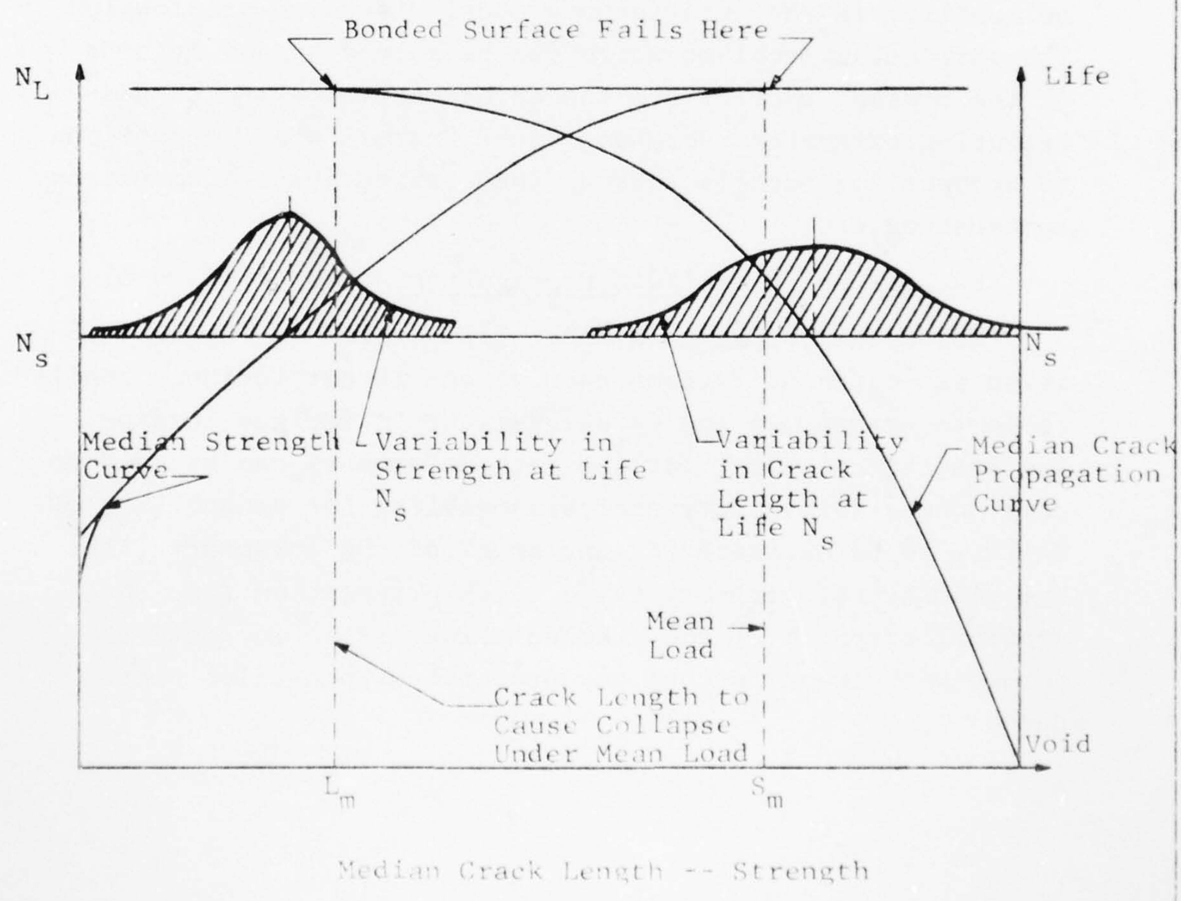


Figure 4-16

THE RISK OF STRUCTURAL FAILURE BY FATIGUE

Empirical Design Formulas

Applicable to:

- Gear Wear
- Splines
- Joints
- Fasteners (including Bonded Surfaces)
- Slide Bearings

Part manufacturers and suppliers normally provide stress-cycle to failure information in the form illustrated in Figure 4-17. A wide variation in cycles to failure at any design contact stress emphasized the importance of proper part selection in the detailed design phase of a program. If the gear or bearing is designed to perform throughout the life of the component, contact stress should be well below the 10 percent failure limit at the expected life cycle. Relationships have also been developed between critical helicopter performance and reliability parameter. Figure 4-18 illustrates such a relationship for the carbon seal leakage failure mode in various turbine engines. In this case, unscheduled removal is the reliability parameter while seal running speed in the engine is the performance parameter.

Scaling (Ref. 4-6)

Semi-empirical formulas are often used by the design analyst to estimate the life of a new component based on performance of a known similar component. This technique is referred to here as scaling. Scaling can also be used to estimate the failure distribution parameter for a new component, based on a scaling relationship and reliability data on a test component.

The translating equation is:

$n = N(P_1/p_2)^3$ for bearings

$n = N(P_1/p_2)^x$ for gears

where

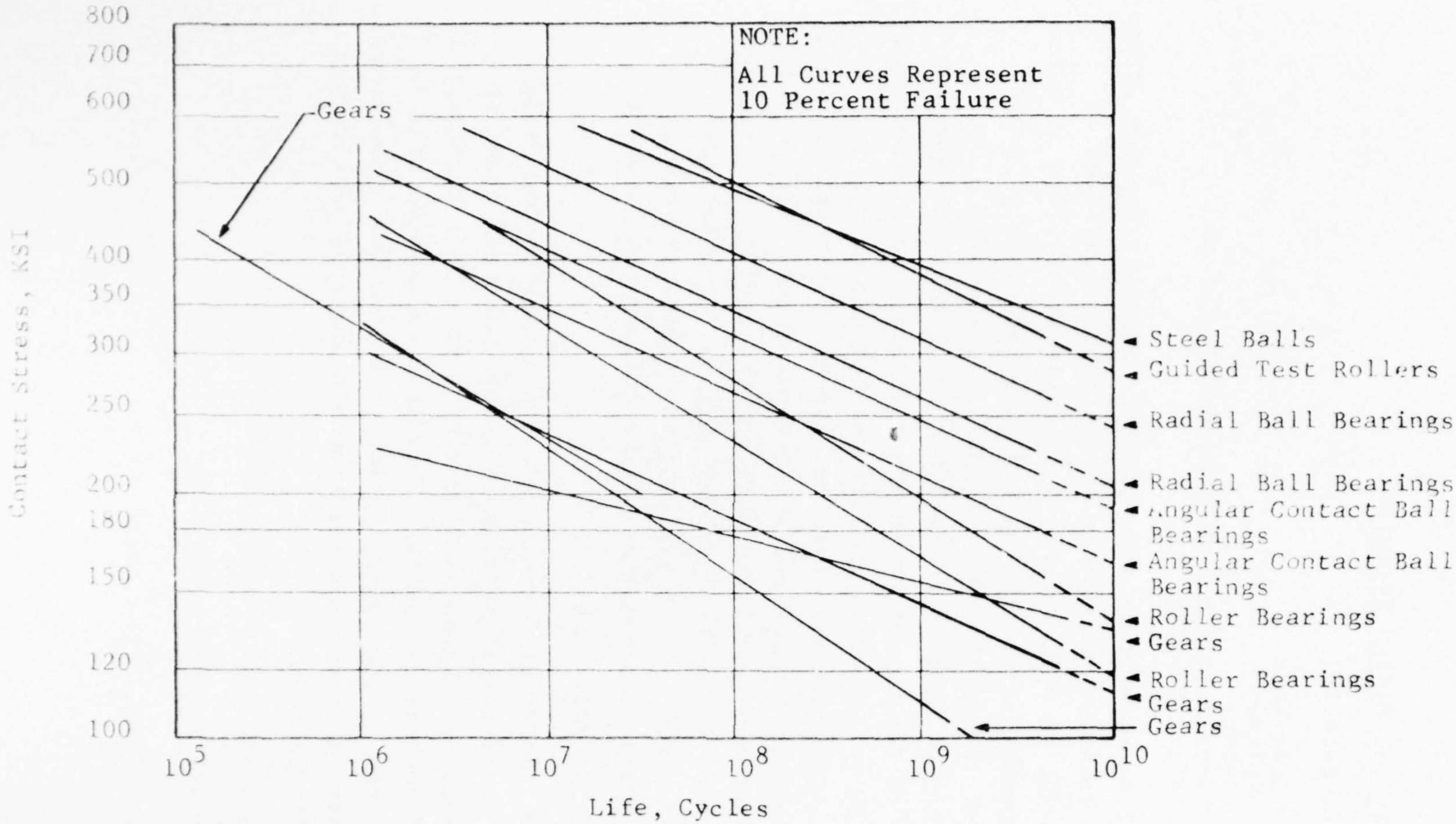


Figure 4-17

S-N CURVES FOR CONTACT STRESS-STEEL MEMBERS

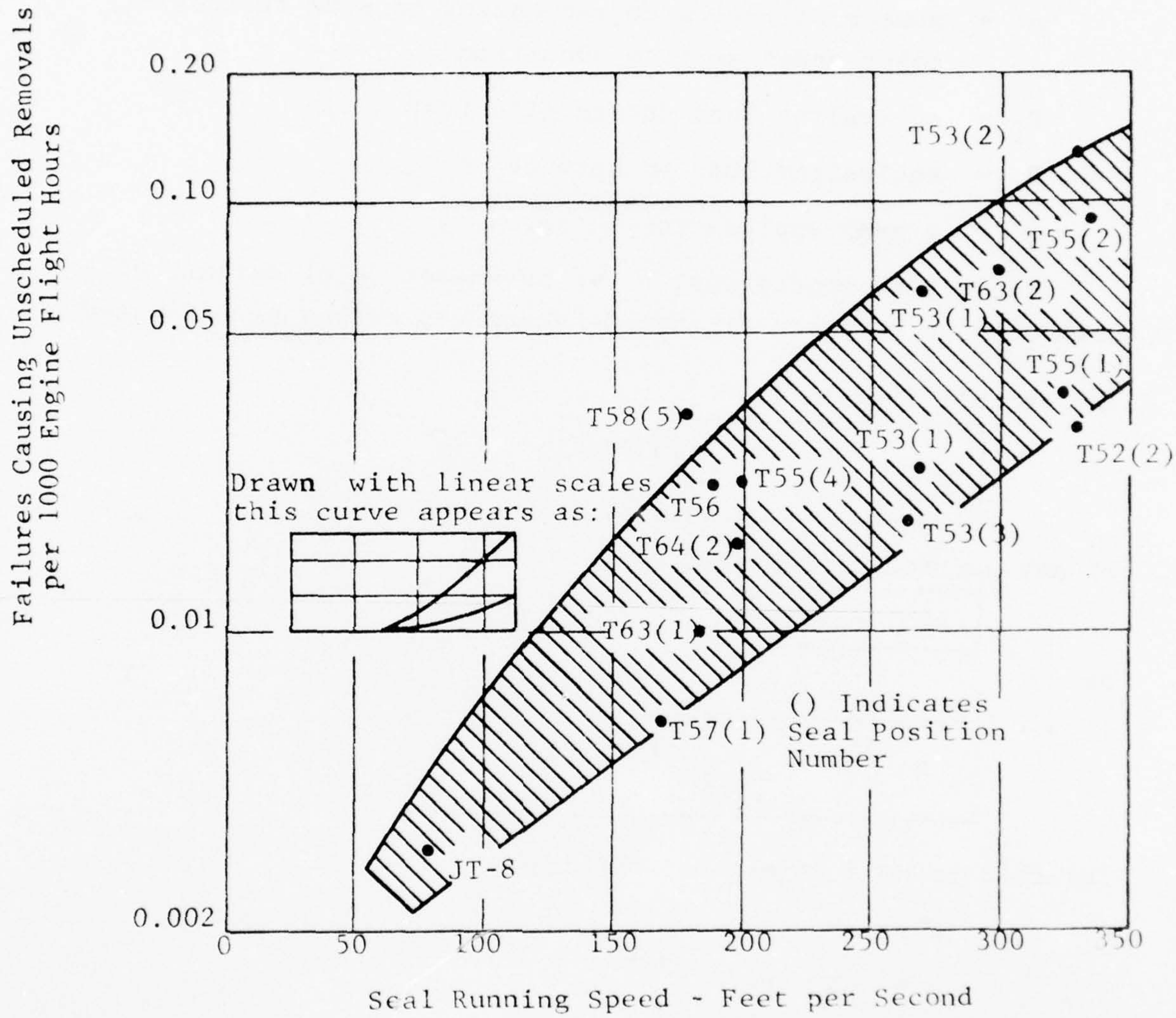


Figure 4-18
CARBON-SEAL RELIABILITY

N = number of cycles corresponding to a specific reliability under test conditions

n = number of cycles corresponding to same reliability point under service conditions

P_1 = equivalent load during life test

P_2 = equivalent load in service

x = a gear application factor

Under test conditions, a two parameter (α, β) Weibull distribution is known to fit the data and α^*, β^* can be estimated.

The Weibull formula is:

$$\boxed{R = \epsilon^{-(t^{\beta})/\alpha} = \epsilon^{-(n^{\beta})/\alpha}}$$

At any particular Reliability

$$\boxed{R(n) = R(N)}$$

or

$$\boxed{\epsilon^{-(N^{\beta^*})/\alpha^*} = \epsilon^{-[N(P_1/p_2)^3]^{\beta}/\alpha}}$$

for this to hold at all reliabilities.

$$\beta = \beta^*$$

$$\alpha = \alpha^* \quad (p_2/P_1)^{3\beta^*}$$

With the above formula it is possible to estimate the new reliability under a particular load condition (p) and cycle time (n).

4.3.2.3 Reliability Allocation Technique (Reference 4-7)

Once a system reliability requirement has been established, it will usually be necessary to apportion the overall reliability among several subsystems. Several basic techniques are available for allocating system reliability to the subsystems.

The particular technique to be applied in a given situation would depend on many factors, such as the amount and type of data available and the overall configuration of the system. Some of the techniques available are described in Figure 4-19, in the order of increasing complexity. It should be noted, however, that the allocation schemes presented here will be valid only to the extent that the final allocated figures are achievable by the components to which they are assigned. If reliability allocations are not achievable redundancy may be required to meet the overall system objective. Reliability allocations in redundant systems involve complex modeling proceudres and iterative analysis techniques that are performed to trade-off reliability with cost and weight penalties. Such techniques are beyond the scope of this section and will not be discussed here. However, some of the procedures mentioned in Section 5.0 for cost trade-off techniques are similar to the procedures that would be used in these complex allocations.

4.3.2.4 Reliability Assessment Using Bayesian Statistics

The Bayesian methodology is gaining increasing prominence in the areas of statistical analysis and decision making, and, although known for some time, it is only now gaining wider use in the field of reliability analysis.

The recognized usefulness of Bayesian statistics is that it provides a methodology for allowing prior information concerning a random process to be integrated with more current test data or other updated information, thus yielding a result which utilizes the widest possible range of available information or knowledge. For example, Figure 4-20 lists the MTBF of components of the hot section module of an engine before and after testing. The prior MTBF could have been analytically computed using reliability prediction techniques. The posterior MTBF is a new estimate of reliability that reflects the test experience but still gives credit to the analytical reliability prediction.

TECHNIQUES	WEIGHTING FORMULA	ALLOCATED SUBSYSTEM RELIABILITY	DEFINITION OF TERMS
Equally critical Subsystems in series cofiguration	None	$R = R_s^{1/n}$	n-number of subsystems R_s-systems reliability
Non-equivalent Subsystems in series configuration	$W_i = \frac{C_i}{C_i + C_2 \cdots C_n}$	$R_i = [R_s]^{W_i}$	C_i-complexity of of ith subsystem
Consideration of Subsystem importance and complexity	$m_i = MTBF_i = \frac{k_i, t_i}{\left(\frac{n_i}{N}\right)(-\ln R_s)}$	$R_i = 1 - k_i(1 - e^{-t_i/m_i})$	k_i-probability system fails if i fails n_i- number of components in ith subsystem

Figure 4-19

RELIABILITY ALLOCATION TECHNIQUES (Ref. 4-7)

Components	Prior MTBF (Hours)	Operating Hours	Experience Failures	Posterior MTBF (Hours)
Turbine Rotor Assy	24510	1487.5	1	19493
Combustion Liner	13889	1370.6	1	11820
Stage 1 Turbine Nozzle	15432	1335.2	0	16234
Stage 2 Turbine Nozzle	35971	1335.2	0	37453
TOTAL MODULE	4869	1382.1	2	4460

Figure 4-20

HOT SECTION MODULE EXPERIENCE

The Bayesian formula is used to update probability prediction with new information. The formula is normally written in discrete probability terms as

$$\boxed{P(A|B) = \frac{P(A)\ P(B|A)}{\sum_{A} P(A)\ \ P(B|A)}}$$

Figure 4-21 is an illustrative example using the Bayesian formula with the probability terminology defined. Note that the posterior probability represents a discrete distribution. What is desired is a reliability point estimate. It is possible to obtain a reliability estimate by defining a loss function which is associated with an incorrect estimate. Also, prior and present information could be weighted to reflect their importance. For standard continuous distributions both loss functions and weighting factors were applied, and the following formulas were obtained:

1. Normal Distribution--Suppose the mean (μ) is to be estimated, and the prior distribution of μ is said to come from a normal distribution also. If the loss function is $(\mu-\mu^*)^2$, then the Bayes estimate of μ is

$$\boxed{\mu^* = \frac{n\bar{X} - n\mu_o}{2n}}$$

where n is the sample size; $\bar{X}$, the mean from the sample; and μ_o, the prior estimate of μ.

2. Poisson Distribution--Suppose the mean (λ) is to be estimated, and the prior distribution of λ is estimated to come from a Gamma distribution. If the loss function is $(\lambda-\lambda^*)^2$, then the Bayes estimate of λ is

$$\boxed{\lambda^* = \frac{2x}{x/\lambda_o + T}}$$

$$P(A/B) = P(A) \frac{P(B/A)}{\Sigma P(A)\ P(B/A)}$$

A	P (A)	B Test Result T	B Test Result F	P (B/A)	P (A) P (B/A)	P (A/B)
.5	.25			.5	.1250	.6173
.8	.25	1	1	.2	.0500	.2469
.9	.25			.1	.0250	.1235
.99	.25			.01	.0025	.0123
					Σ .2025	

A = a hypothesis or statement of belief. ("The reliability of this component is 0.50 or 0.90.")

B = a piece of evidence, such as a reliability test result which as bearing upon the truth or credibility of the hypothesis. ("The component failed on a single mission trial attempt, T = No. of tests and F = failures.")

P (A) = the <u>prior</u> probability, or the probability we assign to the hypothesis A before evidence B becomes available.

P (B/A) = the <u>likelihood</u>, or the probability of the evidence <u>assuming given</u> the truth of the hypothesis. ("The probability of the observed failure, given that the true component reliability is indeed 0.90, is obviously 0.10.")

P (B) = the probability of the evidence B, evaluated over the entire weighed ensemble of hypothesis A.

P (A/B) = the <u>posterior</u> probability of A <u>given</u> the evidence B.

Figure 4-21

ILLUSTRATIVE EXAMPLE OF THE BAYESIAN FORMULA

where T is the time interval of the test, x the number of occurences in time T, and λ_o the prior estimate of λ.

3. Exponential Distribution -- Suppose the mean (θ) is to be estimated and the prior distribution of θ is said to come from a Gamma distribution. If the loss function is $(\theta-\theta^*)^2$, then the Bayes estimate of θ is

$$\boxed{\theta^* = \frac{2}{1/\theta_o + \bar{t}}}$$

where $\bar{t}$ is the observed average time between occurences and θ_o is the prior estimate of θ.

θ is actually the failure rate of the component, and MTBF = $1/\theta$.

Further utility of the Bayesian technique may be demonstrated for the case where current information may be in the form of an updated reliability estimate based upon a higher level of more selected information, rather than being in the form of test data per se. To illustrate, the Bayesian technique may be helpful in combining reliability estimates from a prediction-by-function technique early in the system development, with a later reliability estimate based upon a detailed stress-analysis.

4.3.3 Maintainability Prediction, Allocation and Assessment

Techniques important to the successful implementation of maintainability in the design of a new helicopter are discussed in this section. Implementation of these techniques in any specific helicopter program would depend on the level of maintainability specified, fielded maintenance policies and philosophy, scheduling factors and cost constraints.

Maintainability predictions, like reliability predictions, are performed after the basic system has been defined. It is at this stage that sufficient engineering data is available to perform a meaningful quantitative evaluation of design characteristics in terms of performance, serviceability, and support. Predictions can provide an indication of compliance with specified maintainability requirements (e.g., MTTR, MDT, Mean Time Between Maintenance Actions (MTBMA), etc.), and provide a level of confidence for successfuly completing maintainability demonstrations.

Maintainability allocation is closely related to maintainability prediction in that once the overall requirements for the system has been determined in terms of MTTR, it is apportioned separately down to each subsystem/assembly in the design. This is accomplished in such a manner that upon completion of the design, the statistical mean of all the subsystem MTTR's will be less than or equal to the MTTR required of the total system.

Maintainability assessments are performed as are the predictions, during and after system definintion. The basic function of M assessment is to provide definite system and equipment design requirements, based on operational and maintenance requirements outlined in the contract. Therefore, the assessment should provide a definite listing of M requirements for the system design, a list of criteria that will insure the requirements have been met, and a list of the maintenance functions required for the system.

In actual application, there is considerable overlap between prediction and allocation. An allocation, ususally performed early in the developmental stage, helps to outline a design approach for meeting a system maintainability objective. Predictions are performed as the design progresses, as a measure of compliance to these objectives.

4.3.3.1 Maintainability Prediction (MIL-HDBK-472)

The maintainability prediction techniques discussed in the following section are basically outlined in MIL-HDBK-472, "Maintainability Predictions", 24 May 1966.

The prediction process in its simplest, consists of four basic steps for the calculation of MTTR parameters.

Step 1 - Preparing a functional-level diagram
Step 2 - Determining repair time
Step 3 - Collecting failure rate data
Step 4 - Computing MTTR

A sample functional-diagram is shown in Figure 4-22. This diagram is based on the OH-58 helicopter. It should be noted that this diagram represents only the engine and related system portion of the OH-58 helicopter. This diagram was prepared to illustrate the technique and does not necessarily reflect an actual functional level breakdown of the helicopter engine system. The actual diagram for a helicopter system or component must be structured through a detailed review of the equipment's design characteristics and maintenance features. The technique invovles dividing the system and its equipment items into its various physical subdivisions down to the lowest item that will be replaced during corrective maintenance.

Each branch of the diagram is terminated with a circle which indicates the item(s) that will be replaced to correct failures existing in that branch. For example, the corrective maintenance level for the engine is primarily at the subsystem level as shown in Figure 4-22, and the corrective maintenance level of the engine related system is at the assembly/component and part level. The diagram, once completely structured for the system, will reflect the overall maintenance concept and the complete replacement breakdown for all equipment items that comprise the system.

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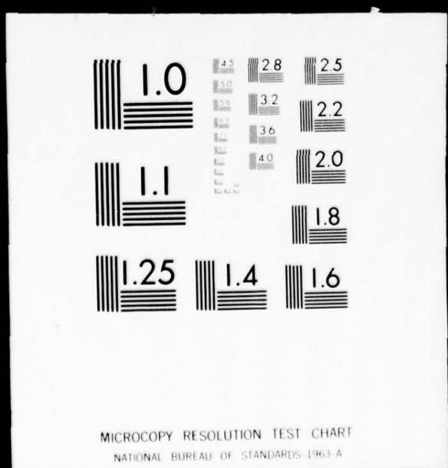

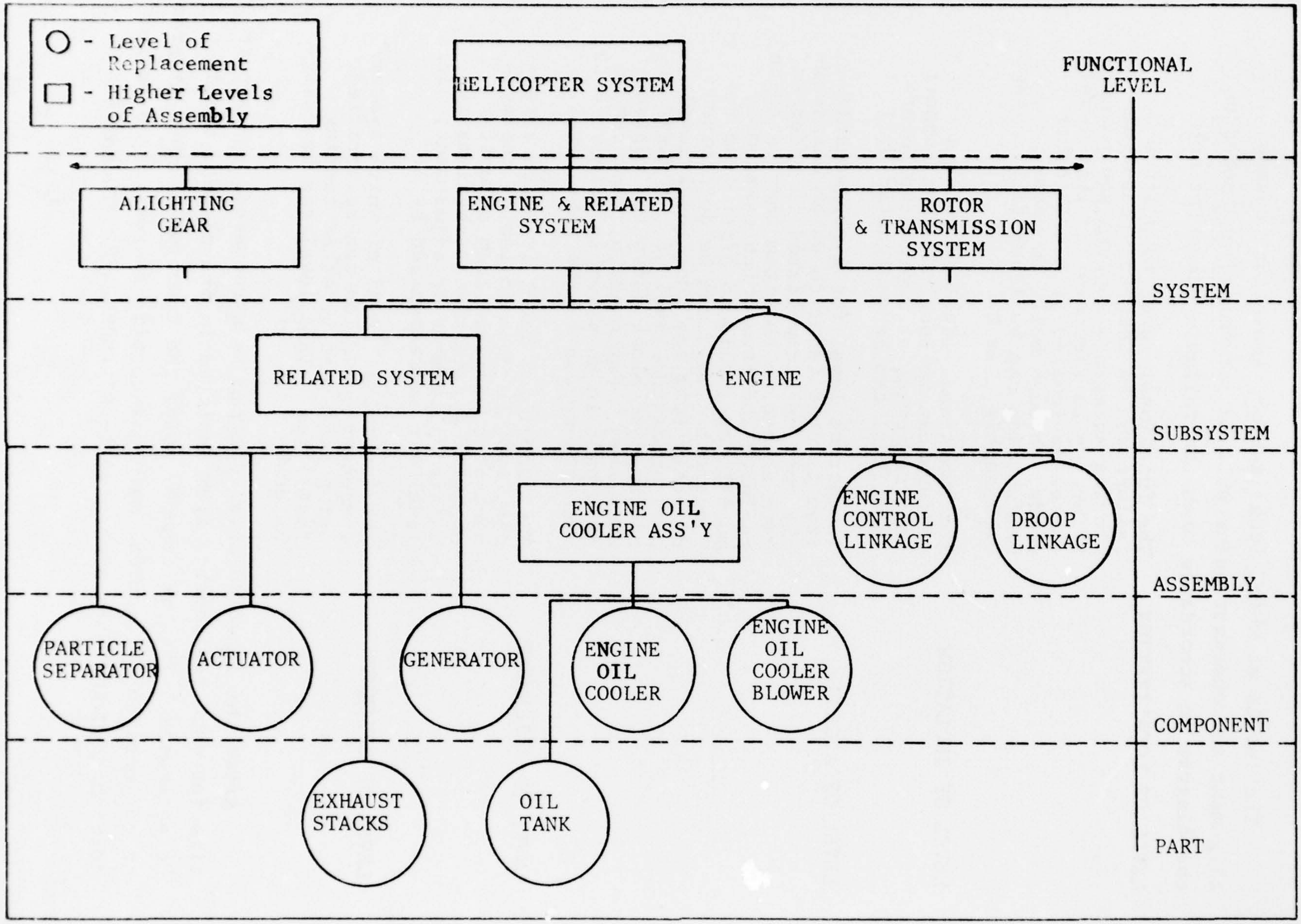

Figure 4-22
SIMPLE FUNCTION-LEVEL DIAGRAM
(ENGINE AND RELATED SYSTEMS)

The levels at which localization, isolation, access, alignment and checkout occur will be determined and noted on the diagram in accordance with the following description:

LEVEL OF LOCALIZATION	The functional level to which a failure can be located without employing accessory support equipment. Referring to Figure 4-22, this level can be designated by L. In other words, through built-in means, a malfunction can be identified to the replaceable item L.
LEVEL OF ISOLATION	The functional level to which a failure can be located using support test equipment at designated points. This level can be designated by I.
LEVEL OF ACCESS	The access level for a replaceable item is that level to which disassembly must be accomplished in order to gain access to the item that is to be replaced and from which reassembly must be accomplished after item replacement. This can be determined directly from the functional level diagram as the level of the first rectangular block above the replacement item. For example, replacement of a part in an assembly (Figure 4-22) requires access to the part level.
LEVEL OF ALIGNMENT	The functional level at which alignment must be done following replacement of a variable item or unit containing sensitive mechanisms requiring alignment or adjustment. This level can be designated by A.
LEVEL OF CHECKOUT	The functional level at which system/component operation can be verified using self-test or other testing facilities. This level can be designated by C.

After the function-level diagram is structured, the repair time for each replaceable item depicted in the diagram should be estimated. This is done by using the functional level diagram in conjunction with actual maintenance time factors, or average maintenance time data presented in MIL-HDBK-472. These time

estimates are to take into account the maintenance characteristics of the system as reflected in the function-level diagram. For example, total diagnostic time (localization and isolation time) would be short if the function-level diagram indicates, for a given item, that a malfunction can be localized to the level of replacement. However, diagnostic time would be considerably longer if the diagram indicates that several isolation levels exist between localization and replacement. Finally, failure rates for each replaceable item are assigned and used in calculating the MTTR.

MIL-HDBK-472 provides four specific procedures for maintainability prediction using the basic concepts described below, which are applicable to a wide variety of systems. While Procedures I and III apply only to electronic systems, Procedures II and IV are useful for any type of system. All procedures depend on the use of R&M data which may have to be obtained from comparable systems under similar use and operating conditions. Using data of this nature requires one to assume that data accumulated for an existing system will be representative of the results one will achieve on the system under development. This procedure can be justified when there is a sufficient degree of commonality between the systems. This commonality often exists when one compares systems on general terms during the early stages of development. However, extra effort is required during later design stages to insure that commonality exists in terms of equipment functions, maintenance task times, and levels of maintenance. If historical data is not available from similar applications, it may be necessary to acquire it by using theoretical relationships, by simulation exercises, or from estimates based on expert judgment.

Procedures I, II, III, and IV of MIL-HDBK-472 (24 May 1966), "Maintainability Prediction", are briefly outlined in Figure 4-23 and described in the paragraphs following. A more complete explanation can be obtained from the referenced handbook.

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PROCEDURES	I	II	III	IV
Applicability	To predict flight-line maintenance of airborne electonic and electro-mechanical systems involving modular replacement.	To predict the maintainability of electronic equipment and systems. It can also be used to predict the maintainability of mechanical systems provided that required task times and functional levels can be established.	To predict the mean and maximum active corrective maintenance downtime for ground electronic systems and equipment. It may also be used to predict preventive maintenance time.	To predict the mean and/or total corrective and preventive maintenance downtime of systems and equipments.
Point of Application	After establishment of the design concept provided that data as listed in the column entitled "Information Required" is available.	Applicable during the final design stage.	Applicable during the Design Development and Control Stages.	Applicable throughout the design development cycle with various degrees of detail.
Parameters	System downtime including logistics and administration time.	Mean corrective maintenance time Mean preventive maintenance time Mean active maintenance manhours	Mean and Max corrective time Mean and Max preventive time Mean downtime	Mean systems downtime Mean corrective downtime/operation Total corrective downtime/operation Total prevention downtime/operation
Methodology	Multiple regression analysis.	Experienced diagnostic and repair time.	Linear regression analysis check list.	Experienced diagnostic and repair time.
Level of Analysis	Modular Assembly	Part Subassembly Assembly Unit Equipment Subsystem System	Part Subassembly Assembly Unit Equipment Subsystem System	System

Figure 4-23

MAINTAINABILITY PREDICTION PROCEDURE CHARACTERISTICS

PROCEDURE I

This procedure has been developed for use in predicting system downtime of airborne electronic and electro-mechanical systems involving modular replacement at the flight-line. It was developed using maintenance data from repairs on the AN/ASB-4 Bombing and Navigation System on the B-52 bomber. The procedure was tested with satisfactory results on seven other systems. (These systems are identified and the results shown in MIL-HDBK-472.) It is therefore anticipated that this prediction procedure will give satisfactory results when it is applied to systems similar to those tested and referenced in MIL-HDBK-472.

The procedure itself is built around "Elemental Activity" times which are fundamental elements of downtime from which other more comprehensive measures of downtime are developed. An Elemental Activity is defined as a simple maintenance action of short duration and relatively small variance which does not change much from one system to another. Typical examples would be the opening of an equipment compartment or checking maintenance records. An extensive listing of these Elemental Activities along with associated time distributions are given in MIL-HDBK-472. The activities in this listing have been broken into five categories. They are:

1. Preparation Time
2. Malfunction Verification Time
3. Fault Location Time
4. Part Procurement Time
5. Repair Time

The times in these various categories along with information concerning "Final Malfunction Test Time" are combined step-by-step and used to build up a "Total System Downtime." The progression of this building up process through several steps is graphically illustrated in Figure 4-24.

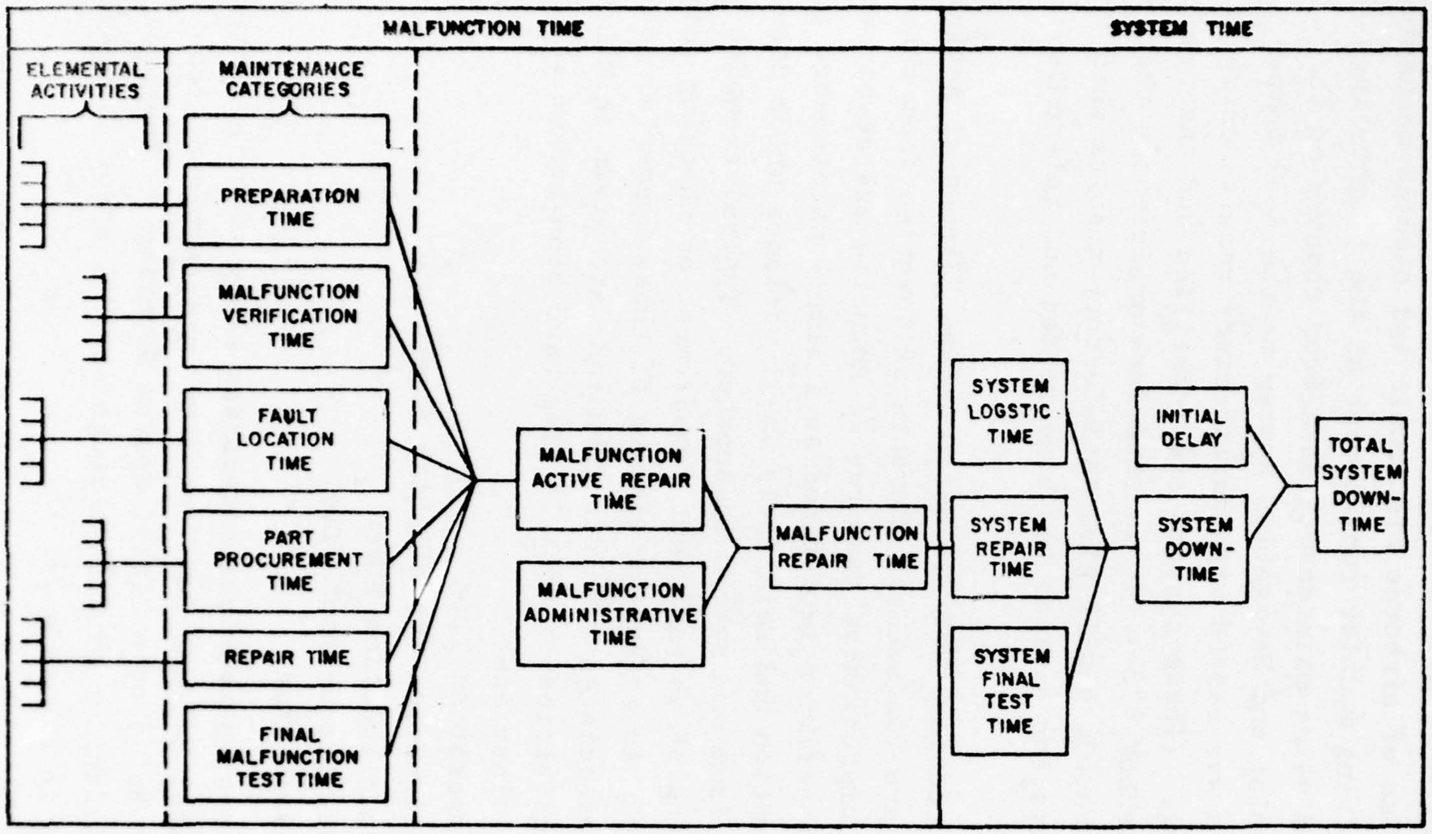

Figure 4-24

BUILD UP OF TIME ELEMENTS (from MIL-HDBK-472)

Procedure I actually yields only "System Downtime" and does not provide the "Total System Downtime" that is shown in Figure 4-24. In this sense the procedure stops short of a total predicted time value that starts when the malfunction is reported.

A rather laborious manual Monte Carlo procedure is outlined to accomplish the build up of elemental times into a distribution of system downtime. Successful application of this Monte Carlo procedure depends on (1) an accurate description of the distribution of time required for the performance of an Elemental Activity, and (2) the probability of occurrence of an Elemetal Activity. The distribution of time has been found to be independent of the type or design of the system involved and are specified for each Elemental Activity specified in the procedure. However, the probability of occurrence is related to various design parameters and a method is given for acknowledging this relationship and calculating these probabilities.

Both the distributions of activity times and their probabilities of occurrence are used by the Monte Carlo procedure to produce a predicted distribution of system downtime.

Procedure II

This procedure was first developed to predict the maintainability of electronic systems. A claim is made in MIL-HDBK-472 that it can also be used to predict the maintainability of mechanical systems provided that required task times and functional levels can be established. While this claim is true in theory, it is substantially weakened by the fact that the procedure describes all functional levels and tabulates all element times in terms of electronic equipment.

Procedure II consists of prediction methods which can be used during the final design stage of a product to predict corrective, preventive and active maintenance procedures. (Corrective and preventive maintenance predictions include only actual repair time when the equipment under repair is shut down. Active maintenance predictions combine both corrective and preventive maintenance.) In addition, there are two distinct and different approaches within Procedure II that can be used for predicting maintenance times. Both approaches require the analyst to develop a description of the maintenance tasks under study. Times are then applied to various elements of these descriptions, summed up and combined with failure rate information to arrive at a predicted maintenance time.

The maintenance task descriptions are in terms of the functional level at which repair takes place and in terms of generalized maintenance tasks. The different functional levels are a recognition that repair time is dependent on the level at which the repair is accomplished. The levels used in Procedure II are:

Part
Stage
Subassembly
Unit

Group
Equipment
Subsystem
System

The maintenance tasks which can be accomplished at each of these levels have been categorized as:

Localization
Isolation
Disassembly
Interchange
Reassembly
Alignment
Checkout

The first approach (Approach A) relies on the use of predetermined maintenance times for assigning times to elements of the above descriptions. These predetermined times apply to corrective maintenance only and come from two sources. The primary source consists of tabulated data compiled as a result of over 300 observations of maintenance activity in the U.S. Navy fleet. This data is supplemented with predetermined time standards developed by using the Work-Factor* synthetic basic motion time system.

The second approach (Approach B) uses estimated times as determined by the analyst for assigning times to elements of the described maintenance tasks. This approach is quite subjective and requires a thorough understanding of equipment groupings, diagnostic and repair methods, etc., on the part of the analyst. Times are estimated for both corrective and preventive maintenance and are eventually combined to determine the mean man hours of active maintenance time.

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* Trademark.

Procedure III

This procedure has been developed for use in predicting the mean and maximum corrective maintenance downtime of ground electronic systems. It can be used during the design and development stage. The basic assumptions upon which it is based are:

1. System downtime is principally due to the failure of replaceable items.

2. Length of system downtime is a function of specific design parameters which govern replacement time. These parameters are:

   (a) Physical configuration of the system
   (b) Facilities provided for maintenance
   (c) Degree of maintenance skills required to replace the failed item.

3. Similar classes of equipment require a similar type of maintenance activity when repair by replacement is used.

4. Uniformity of design within a class of equipment will permit the use of a random sample of replaceable items to establish repair times for the entire class.

The basic procedure consists of the following steps:

1. Select a random sample of replaceable items.

2. Conduct a maintainability analysis for every item in the sample.

3. Assign a "score" to each maintenance task associated with a sample item. This is done with the aid of design check lists that provide scoring criteria.

4. Convert scores to downtime through the use of an equation given in the procedure.

These steps are explained in more detail.

A total sample of size N is randomly selected and includes parts and components of all classes of items in use. This sample size is dependent upon the statistical accuracy desired in the final results and is obtained by use of the equation

$$\boxed{N = \frac{\sigma}{\bar{X}} \left(\frac{Z}{K}\right)^2}$$

where

Z = the normal deviate corresponding to the desired confidence level

σ = the population standard deviation of the mean time to repair

$\bar{X}$ = the population arithmetic mean time to repair

K = the desired accuracy of the prediction, given as a percent of the mean $\bar{X}$.

This equation may be rewritten as

$$\boxed{N = C_X\left(\frac{Z}{K}\right)^2}$$

where

$$C_X = \frac{\sigma}{\bar{X}}$$

and is called the coefficient of variation. Note that this measure of relative variation, C_X, is simply a ratio and is independent of the scale of measurement and can therefore be used to relate or compare the variation in several sets of data. Field experience with ground electronic equipment has shown that when applied to this procedure a good practical estimate for C_X should be used if adequate data is available reflecting experience with systems similar to the one under study.

Determination of the total sample size N is illustrated with the following example. Assume that one wishes to be 95% confident that he can predict the MTTR within an accuracy of ± 30%. The normal deviate, Z, corresponding to a 95% confidence interval is 1.960. Substituting these values along with C_X = 1.07 into the equation for N, one obtains

$$N = 1.07\left(\frac{1.960}{.30}\right)^2 \approx 49$$

which for convenience will be rounded up to 50.

As was stated earlier, this sample of size N includes replaceable parts and components of all classes of items. It is now necessary to break down the total sample of size N into task sub-samples (M) with each sub-sample representing a given class of replaceable items. The procedure of breaking down a total sample of size N can best be shown by using an example taken from MIL-HDBK-472. In this example a sample of size N=50 will be used on a system containing replaceable items that fall into ten classifications. These classifications and the number of items in each classification are shown in the first two columns of Figure 4-25. The item failure rate in failures per million hours must then be determined and shown in Column 3 of Figure 4-25. The expected number of failures due to each class is then determined in Column 4 and the contribution each class of items makes to the total expected number of failures is obtained in Column 5. The number of failures (or maintenance tasks) in a sample of size N=50 is then determined in Column 6 and is rounded to the nearest whole number in Column 7. At this point one is ready to select randomly from each part class enough items to meet the requirements for task sub-samples specified in Column 7.

(1) Part Class	(2) Quantity	(3) Average Part Failure Rate 10^6 Hours	(4) Expected Number of Failures per 10^6 hrs (2) x (3)	(5) Contribution to Total Expected Failures (%) (4) ÷ 7280.46	(6) No. of Failures for Sample Size, N = 50 (5) x (50)	(7) Actual Class Sample used $_\eta$
Motor	25	1.89	47.25	.65	0.3	0
Capacitor	1280	0.100	128.00	1.76	0.9	1
Diode	4	29.83	119.32	1.64	0.8	1
Connector	335	0.320	107.20	1.47	0.7	1
Relay	43	3.59	154.37	2.12	1.1	1
Coil	349	0.330	115.17	1.58	.8	1
Resistor	2459	0.150	368.85	5.07	2.5	2
Switch	162	0.450	72.90	1.00	.5	1
Transformer	160	1.33	212.80	2.92	1.5	1
Tube	380	15.67	5954.60	81.79	40.9	41
TOTAL	5197		7280.46	100%		50

Figure 4-25

PART CLASS FAILURE DISTRIBUTION AND SAMPLE SIZE

A scoring sheet must now be completed for each item selected by the above sampling procedure. This is the most difficult and at the same time the most important step of the entire procedure. The analyst must be thoroughly familiar with the functional operation of the equipment, its failure modes, diagnostic and maintenance procedures, and the tools or test equipment required to carry out these procedures. Once this familiarity is achieved, the analyst is ready to complete the scoring sheets and assign a score to each maintenance task associated with a sample item. An example of one factor affecting maintenance time and its scoring criteria is shown in Figure 4-26.

There are thirty-two factors similar to the one shown in Figure 4-26 that affect maintenance time and all must be completed for each item in the random sample. These factors are divided into the three categories or areas which cover:

1. Physical configuration of the system (A)
2. Facilities provided for maintenance (B)
3. Degree of maintenance skills required to replace the failed item (C).

The total of the scores for a given class of equipment in each of the above three areas are then substituted in the linear regression equation

$$M_{ct} = \text{ANTILOG}[3.54651 - 0.02512A - 0.03055B - 0.01093C]$$

where

M_{ct} = corrective maintenance time of individual maintenance tasks

A = score relating to physical configuration

B = score relating to facilities provided

C = score relating to the degree of maintenance skills required to replace a failed item of a given class.

Latches and Fasteners (External): Determines if the screws, clips, latches, or fasteners outside the assembly require special tools, or if significant time was consumed in the removal of such items. Scoring will relate external equipment packaging and hardware to maintainability design concepts. Time consumed with preliminary external disassembly will be proportional to the type of hardware and tools needed to release them and will be evaluated accordingly.

Scores

(a) External latches and/or fasteners are captive, need no special tools, and require only a fraction of turn for release . . . 4

(b) External latches and/or fasteners meet two of the above three criteria 2

(c) External latches and/or fasteners meet one or none of the above three criteria 0

Scoring Criteria

(a) To be scored when external screws, latches, and fasteners are:

(1) Captive
(2) Do not require special tools
(3) Can be released with a fraction of a turn

Note: Releasing a "DZUS" fastener which requires a 90 degree turn using a standard screw driver is an example of all three conditions.

(b) To be scored when external screws, latches, and fasteners meet two of the three con conditions stated in (a) above. An action requiring an Allen wrench and several full turns for release shall be considered as meeting only one of the above requirements.

(c) To be scored when external screws, latches, and fasteners meet only one or none of the three conditions stated in (a) above.

Figure 4-26

EXAMPLE OF FACTOR AFFECTING MAINTENANCE TIME AND THE FACTOR'S SCORING CRITERIA

It should be noted that the down time (M_{ct}) yielded by the previous equation presents only the corrective maintenance time associated with a single replaceable item in our sample of size N. The mean corrective maintenance time for the system under study is obtained from the equation

$$\boxed{\overline{M}_{ct} = \frac{\sum_{i=1}^{N} M_{ct}}{N}}$$

where $\overline{M}_{ct}$ is the mean corrective maintenance time for the system and N is the total number of items sampled.

The maximum corrective maintenance time (M_{max}) can now be obtained. M_{max} is expressed as

$$\boxed{M_{max} = \text{antilog}\left[\overline{\log M_{ct}} + 1.645\sigma \log M_{ct}\right]}$$

where

$$\overline{\log M_{ct}} = \frac{\sum_{i=1}^{N_c} \log M_{cti}}{N_c} = \text{mean of } \log M_{ct}$$

and

$$\boxed{\sigma \log M_{ct} = \sqrt{\frac{\sum_{i=1}^{N_c} (\log M_{cti})^2 - (\sum_{i=1}^{N_c} \log M_{cti})^2/N_c}{N_c - 1}}}$$

The coefficients for the above equations were derived from 101 corrective maintenance tasks associated with the AN/FPS-2 long range radar, AN/FST-2 two channel data processor and AN/GKS-5 data link transmitting equipment.

The correlation between predicted values and actual values of corrective maintenance downtime was found to be good provided adequate information was available and mature experienced analysts were used. Results of some actual correlation studies are presented in MIL-HDBK-472.

Procedure IV

This is a very general and theoretical procedure and has been developed to provide maintainability predictions on any type of system. While this generality is an asset in one sense it is also a liability in that the procedure does not provide a great deal of specific guidance in arriving at useful maintenance times. The procedure states that existing data should be used to the extent possible but does not provide any data nor does it reference any sources. The main contribution made by Procedure IV of MIL-HDBK-472 is a structured framework within which specific maintenance times can be estimated and then combined to yield a prediction of interest. The predictions possible from using this procedure are:

(a) The elapsed time to perform preventive maintenance action, assuming that no detectable malfunctions exist in the system.

(b) The elapsed time to correct malfunctioning end items detected during each preventive maintenance action of an operational function.

(c) The distribution of corrective maintenance times for detectable malfunctioning end items for each preventive maintenance action of an operational function.

(d) The mean corrective downtime (MCDT) for detectable malfunctioning end items for each preventive maintenance action of an operational function.

(e) The distribution of corrective maintenance task times for the system and subsystems.

(f) The preventive downtime (PDT) for the system and subsystems for a specified calendar time.

(g) The total mean corrective downtime (MCDT) for the system and subsystems for a specified calendar time.

(h) The total mean downtime for integrated preventive and corrective maintenance for the system and subsystems for a specified calendar time.

The procedure itself focuses on end item maintenance task analysis. It necessitates a great deal of mature judgement on the part of the analyst and requires the following information to make the initial maintenance task time analysis.

(a) System Block Diagram
(b) Functional Flow Diagrams
(c) Subsystem Block Diagrams
(d) Subsystem Flow Diagrams
(e) End Item List
(f) End Item Failure Rates
(g) Maintenance Concept
(h) Maintainability Goals
(i) Operational Resources (facilities, personnel, support equipment, etc.)
(j) A detailed definition of the task being performed
(k) Location at which the task is being performed
(l) Environmental Constraints.

End items are identified down to the smallest piece of equipment on which a specific maintenance action will be accomplished. The failure rate for each end item is then identified along with the preventive and corrective maintenance actions to be performed on the item. A task analysis is conducted for all maintenance actions to determine the troubleshooting, repair, and verification time for each end item. The resulting preventive and corrective maintenance times along with their associated frequency of occurrence are then integrated over a previously specified calendar time to derive the total preventive downtime, total mean corrective downtime, and the total mean downtime.

The theoretical formulation and structure of the procedure taken from MIL-HDBK-472 is given with specific notation defined as follows:

I = End item of the system

λ = Failure rate of an end item

P = Preventive maintenance action

C = Corrective maintenance action

O = Operational function of the system.

The task times for preventive maintenance actions are given by:

$$PDT_m = \sum_{i=1}^{m} T_{i_m}$$

where

PDT_m = the total preventive maintenance performance time for action P_m

T_{i_m} = the time to perform the maintenance task on end item I_i as required by action P_m

Thus for action P_m:

$$\text{Item 1:} \quad T_{1_m} = (\Sigma T_{s_{1_m}}) + T_{c_{1_m}} + T_{v_{1_m}}$$

$$\text{Item 2:} \quad T_{2_m} = (\Sigma T_{s_{2_m}}) + T_{c_{2_m}} + T_{v_{2_m}}$$

$$\text{Item n:} \quad T_{n_m} = (\Sigma T_{s_{n_m}}) + T_{c_{n_m}} + T_{v_{n_m}}$$

$$\text{Item } i^{th}\text{:} \quad T_{i_m} = (\Sigma T_{s_{i_m}}) + T_{c_{i_m}} + T_{v_{i_m}}$$

where

T_{i_m} = the total time required to correct malfunctioning end item I_i during action P_m of an operational function.

$T_{s_{i_m}}$ = the troubleshooting test times required to isolate end item I_i during action P_m

$T_{c_{i_m}}$ = the time required to remove, replace, adjust, or otherwise repair malfunctioning end item I_i during action P_m

$T_{v_{i_m}}$ = the time required to verify that the system is good, given that I_i is replaced, repaired, adjusted, etc., during action P_m.

For function O_r:

Item 1: $T_{1_r} = (\Sigma T_{s_{1_r}}) + T_{c_{1_r}} + T_{v_{1_r}}$

Item 2: $T_{2_r} = (\Sigma T_{s_{2_r}}) + T_{c_{2_r}} + T_{v_{2_r}}$

Item n: $T_{n_r} = (\Sigma T_{s_{n_r}}) + T_{c_{n_r}} + T_{v_{n_r}}$

Item i^{th}: $T_{i_r} = (\Sigma T_{s_{i_r}}) + T_{c_{i_r}} + T_{v_{i_r}}$

where

T_{i_r} = the total time required to correct manfunctioning end item I_i during function O_r

$T_{s_{i_r}}$ = the fault isolation test times required to isolate end item I_i during function O_r

$T_{c_{i_r}}$ = the time required to remove, replace, adjust, calibrate, or otherwise correct the malfunctioning end item I_i during function O_r

$T_{v_{i_r}}$ = the time required to verify that the system is good, given that I_i is replaced, repaired, adjusted, etc., during function O_r

In addition, the time to isolate the non-repairable end item groups during action P_m is given by:

$$T_{j_m} = \Sigma Ts_{j_m}$$

where

T_{j_m} = the total time required to isolate the j^{th} group during action P_m of an operational function

$T_{s_{j_m}}$ = the troubleshooting time required to isolate the j^{th} group during action P_m

The mean-corrective-downtime of the system or identification of the requirement to shift it to another maintenance or operational function during action P_m is given by:

$$\boxed{MCDT_m = \frac{\Sigma\lambda_{i_m} T_{i_m} + \Sigma\lambda_{i_{j_m}} \Sigma T_{s_{j_m}}}{\Sigma\lambda_{i_m} + \Sigma\lambda_{i_{j_m}}}}$$

where:

$MCDT_m$ = the mean-corrective-downtime for the system during action P_m of an operational function

λ_{i_m} = the failure rate of detectable malfunctioning end item I_i during action P_m

$\lambda_{i_{j_m}}$ = the failure rate of the i^{th} end item in the j^{th} non-repairable group which can be isolated during action P_m.

The mean-corrective-downtime of the system or identification of the requirement to shift to another maintenance or operational function during function O_r is given by:

$$\boxed{MCDT_r = \frac{\Sigma\lambda_{i_r} T_{i_r} + \Sigma\lambda_{i_{j_r}} \Sigma T_{s_{j_r}}}{\Sigma\lambda_{i_r} + \Sigma\lambda_{i_{j_r}}}}$$

where

$MCDT_r$ = the mean-corrective-downtime for the system during function O_r

$\lambda_{i_{j_r}}$ = the failure rate of the i^{th} end item in the j^{th} non-repairable group which can be isolated during function O_r

A total maintenance time analysis is conducted to define the total time required to perform preventive maintenance, and the total mean-corrective-downtime, for maintenance of the system. The total time for preventive maintenance is given by:

$$\boxed{PDT_t = \Sigma a_m \; PDT_m}$$

where

PDT_t = total preventive-downtime during the specified calendar time

a_m = frequency of occurrence of the m^{th} preventive maintenance action during the specified calendar time.

The mean corrective-downtime for the system is derived from the mission/maintenance profiles. The mean-corrective-downtime for the system is given by the weighted (normalized failure rates) of the MCDT for each action P_m of an O_r operational function. Therefore,

$$\boxed{MCDT_s = \frac{\Sigma(\lambda_{i_r} + \lambda_{i_{g_r}})\; MCDT_r + \Sigma(\lambda_{i_m} + \lambda_{i_{g_m}})\; MCDT_m}{\Sigma(\lambda_{1_r} + \lambda_{i_{g_r}}) + \Sigma(\lambda_{i_m} + \lambda_{i_{j_m}})}}$$

where

$MCDT_s$ = the mean-corrective-downtime for the system for the given mission/maintenance profile.

Applying the equation to a hypothetical mission/maintenance profile results in:

$$\begin{aligned} MCDT_s = \Big[& \Sigma(\lambda_{i_{r_1}} + \lambda_{i_{g_{r_1}}})\; MCDT_{r_1} + \Sigma(\lambda_{i_{m_1}} + \lambda_{i_{g_{m_1}}}) MCDT_{m_1} \\ & + \Sigma(\lambda i_{r_2} + \lambda_{i_{g_{r_2}}})\; MCDT_{r_2} + \Sigma(\lambda_{i_{m_2}} + \lambda_{i_{g_{m_2}}}) + MCDT_{m_2} \\ & + \Sigma(\lambda_{i_{r_s}} + \lambda_{i_{g_{r_s}}})\; MCDT_{r_3}\Big] / \{\Sigma[(\lambda_{i_{r_1}} + \lambda_{i_{r_2}} + \lambda_{i_{r_3}} \\ & + (\lambda_{i_{g_{r_1}}} + \lambda_{i_{g_{r_2}}} + \lambda_{i_{g_{r_3}}})] + \Sigma[(\lambda_{i_{m_1}} + \lambda_{i_{m_2}} \\ & + (\lambda_{i_{g_{m_1}}} + \lambda_{i_{g_{m_2}}})]\} \end{aligned}$$

The total mean-corrective-downtime of the system for the mission/maintenance profile is given by:

$$\boxed{MCDT_t = f(MCDT_s)}$$

where

$MCDT_t$ = the total mean-corrective-downtime of the system for the mission/maintenance profile

f = the number of detectable failures occurring during the calendar time

The total mean-downtime of the system with a specified mission/maintenance profile is given by:

$$\boxed{T_p = \Sigma a_m \, PDT_m + MCDT_t}$$

where

T_p = the total mean-downtime of the system with a specified mission/maintenance profile for the calendar time

a_m = the frequency of occurrence of the action P_m during the calendar period.

The use of a mix of mission/maintenance profiles for the system gives a total mean-downtime of:

$$\boxed{T_t = \frac{\Sigma a_p \, T_p}{\Sigma a_p}}$$

where

T_t = the total mean-downtime of the system for a given mix of mission/maintenance profiles

a_p = the frequency with which the p^{th} mission maintenance profile will occur during the calendar time.

4.3.3.2 <u>Maintainability Prediction (New Concepts)</u>

MIL-HDBK-472, Prediction Techniques, as described in the previous section, are dependent on factors such as diagnostics, packaging, and the failure rates of replaceable parts and components. The repair time data included in MIL-HDBK-472 were derived from early vintage military systems where built in diagnostics and other ease of maintenance features were not incorporated. The repair time data, in general, reflects manual maintenance operations. Today's sophisticated military systems emphasize failure diagnostics, fault isolation, built in test equipment (BITE), modularity and on condition maintenance aids associated with the design. Therefore, current concepts of maintainability require prediction techniques and associated data that account for repairman action times exclusive of modern diagnostic aids, e.g., BITE and fault isolation techniques (FIT). The design of such diagnostic aids has the objective of reducing or eliminating human response time involved in fault location, isolation and checkout. Additionally, in its ultimate application, it reduces the skill level requirement of the maintenance personnel by relieving them of the task and logically deducing proper maintenance action from them.

If "location" and "isolation" are achieved through BITE, the maintenance task is reduced to "removal" and "replacement." If "checkout" is again accomplished through BITE, the impact of BITE on the maintainability has redefined the MTTR more closely with the mean time to remove and replace (MTTR/R). A complete redefinition of MTTR in terms of MTTR/R is hindered by factors restricting design of a perfect BITE. These factors are itemized below:

- Diagnostic Efficiency - The number of possible faults which may occur in equipment is directly related to the number of elements in the system and the number of failure modes for each element. Due to equipment complexity, it is often impossible to associate a fault signal with each element and failure mode. The restrictions imposed on BITE in achieving location and isolation

of all conceivable failures are complexity, cost, reduced reliability and weight. Cost is optimized as a function of BITE complexity, reliability and weight resulting in less than completer fault location and isolation. Efforts are presently underway to develop a prediction procedure accounting for repair action times associated with location, isolation and checkout of faults not identifiable with BITE.

- Ambiguity - The location and isolation of a particular fault requires detection of an error signal unique to that fault and unique to the element in which that fault occurs. In many instances, compromises must be accepted in application of FIT. As described above, complexity of the system may prohibit a one to one correspondence between elements and fault indicators, but unlike the problem of diagnostic inefficiency, a fault indication may be observed for one of several elements. In this circumstance, ambiguity exists and complete isolation to a particular element is not achievable through FIT alone. Ambiguity may occur for other reasons as well. (1) A complex military system is composed of a variety of elements, several of which may involve similar responses when at fault; (2) an element may have several failure modes, some of which exhibit responses identical to failure modes of dissimilar elements. The complete elimination of ambiguity is a difficult, if not sometimes impossible, task.

The restriction imposed on BITE in reducing ambiguity are similar to those described for diagnostic efficiency. Cost effectiveness in BITE acquisition requires optimization of system parameters with respect to cost resulting in less than maximum achievable reduction in ambiguity. A prediction of maintainability must account for repair times associated with complete fault location and isolation when ambiguity exists. Human action times must be included to identify the actual fault from a subset of conceivable faults identified by BITE.

- BITE Failure - Realization of increased maintainability through BITE requires it having high reliability. Field experience has demonstrated that as high as 30% of operational failures are due to BITE alone. Two modes of failure are conceivable, (1) BITE malfunctions and does not detect a system fault, or (2) BITE malfunctions and indicates a system fault which has not occurred.

In the first mode of failure, a system malfunction would be realized and thought to be due to a fault identifiable by BITE, leading the repairman to checkout system elements not at fault. Since no failure could be found, the failure would eventually be localized to BITE and from there would be isolated.

In the second mode of failure, no system malfunction would be evident, but maintenance time would likely be expended to assure the indicated fault did not exist. No verification of the indicated fault would localize the malfunction to BITE. Additional repair time would then be expended in isolating the fault.

Either mode of BITE failure leads to significant losses in maintainability since considerable repair time is spent in locating and isolating false faults in addition to the time required to repair the BITE.

The restrictions imposed on attainment of BITE reliability are governed by a cost tradeoff between acquisition and support costs. The optimized cost represents the point at which each acquisition dollar spent on increasing reliability will result in exactly a dollar saved in support costs.

Efforts are presently underway to develop improved prediction procedures accounting for BITE unreliability in terms of repair times required to locate and isolate false faults, as well as time required to repair BITE faults.

Current helicopter maintenance practices ultilize an overhaul maintenance philosophy to reduce operational failures. The determination of an optimum time between overhaul (TBO) is based on leaving the equipment in operation as long as possible withough experiencing an in-service failure. This maintenance philosophy is only applicable to parts and equipments exhibiting a repeatable wearout characteristic and should not be used for parts and equipments having a constant failure rate. To be economically feasible, the cost of an in-service failure must be greater than the cost of the scheduled overhual. Therefore, estimation of TBO is also based on evaluation of the cost of in-service failures. In general, for a given aging effect, the higher the cost of an in-service failure, the shorter the TBO. Similarly, for a given in-service failure cost, the more rapidly the failure rate increases with time, the shorter the TBO requirement.

Thus, factors having a predominant influence on the selection of an optimum TBO are the times during which the helicopter is out of commission (awaiting maintenance or having maintenance performed) and resources required to perform the overhaul activity.

One of the advantages of the TBO philosophy is that scheduled overhaul is planned in advance and waiting time is kept to a minimum as opposed to unexpected in-service failures where time will be lost due to being unprepared for the maintenance activity. However, this advantage is limited by a lack of techniques for accurately estimating cost of in-service failures. If the cost is overestimated, the TBO interval is too short. Thus, the actual cost will increase by not taking advantage of the full equipment life. If the cost is underestimated, the TBO interval is too long and actual costs again increase due to more in-service failures.

It can be seen from the previous discussion, that while the TBO philosophy will provide a reduction in maintenance time, inaccuracies in predicting the optimum cost interval for the TBO is a cause for some dissatisfaction.

Therefore, present trends in M have emphasized on-condition maintenance with the goal of providing continuous status of subsystems and the ability to isolate failures to a line replaceable unit (LRU). Implementation of on-condition maintenance requires an on-board system capable of interrogating the operational status of all helicopter subsystems through sensors and transducers installed in the subsystems for operational purposes. The system provides, on-command, fault indications and locations in the form of printed readouts or displays.

The overall objective of on-line maintenance is to reduce the inventory requirement of AGE, spares, manpower, time involved in getting to and from the equipment, etc. Logistically, it eliminates the need to know what equipment is at what base and whether a particular AGE is configured for the next helicopter it will be required to test.

Among the many advantages offered by on-condition maintenance are:

- Immediate failure indication
- Increased flight safety
- Increased mission effectiveness
- Increased availability
- Reduced test time
- Reduced maintenance man hours per flight hour
- Insight into scheduling preventive maintenance
- Reduced incorrect fault diagnosis
- Reduced skill level requirements

Application of on-line maintenance significantly reduces mean time to repair through decreasing fault isolation time and providing a ready source to requalify subsystems after their repair; fewer and less skilled maintenance men are required; no time is required for test equipment set up and disassembly; less time is required for checkout. Decreased delay times normally associated with logistics considerations further reduce mean time to repair. Since all units removed are known to be defective, demand on shop test equipment is reduced and time is not waisted in checking out good equipment and recertifying it after test. Overall this leads to

fewer units in pipeline, a decrease in the number of units which must be stocked and less time wasted in setting up and dismantling units.

The application of on-line maintenance is not without its drawbacks. A system capable of performing the sophisticated functions described above is of sufficient complexity to significantly reduce overall reliability. To remain protected, the penalty paid in decreased reliability must be offset by the increase in probability in mission success achieved through ability to detect failures in flight providing knowledge needed to evaluate helicopter ability to continue the mission.

Other disadvantages include weight, volume and power requirements encountered when adding any hardware to an airborne system. Such penalties must be kept to a minimum through clever design and utilization of existing signals generated in normal subsystem operation.

Effective utilization of the on-condition maintenance concept requires an analysis of the advantages and disadvantages inherent in the application of such a system to helicopters.

4.3.4 Other R&M Evaluation Techniques

4.3.4.1 Failure Mode Analysis

A key task within a well structured R/M program is failure mode analysis. In view of the complexity of aviation systems and the high reliability/safety levels required, the proper application of failure mode analysis is necessary to assure reliability for field use. Failure mode analysis involves determining what parts in a system or component item can fail, the modes of failure that are possible for each of these items, and the effect of each mode of failure

on the complete system or any portion thereof. With respect to design activities, failure mode analysis is a technique for analyzing a design, evaluating the potential manner in which failures can occur, and tabulating results in such a manner that responsible design personnel can consider potential failure modes and their effects (and recommended corrective action) to determine if it is desirable to allocate resources to remove the potential failure mode. In addition, failure mode analysis can be used to investigate actual field failures and determine their impact on mission success and overall reliability.

The systematic identification of potential failures and their effects, using formal analysis techniques, is directly applicable to helicopter systems. The more complex the system the greater the interaction between its constituent components, and the greater the need for a formal and systematic process to identify and classify effects. Specifically, failure mode analysis can be used to:

1. determine needs for redundancy, fail-safe design features, further derating, and/or design simplification;
2. determine the need to select more reliable materials, parts, equipment and/or components;
3. identify single failure points;
4. identify critical items for design review, configuration control, and traceability;
5. provide the logic model required to quantitatively predict the probability of anomalous conditions of the system;
6. identify safety hazard areas;
7. assure that the test program planning is responsive to identified potential failure modes and safety hazards;

8. establish allowable use time or cycles with respect to short-life parts where wearout is dominant;

9. pinpoint key areas for concentrating quality, inspection and manufacturing process controls;

10. establish data recording requirements and needed frequency of monitoring in testing, checkout and mission use;

11. support logistics planning and maintainability analysis by providing information for selection of preventative and corrective maintenance points and development of trouble-shooting guide; and

12. support flight operations activities such as designing fault isolation sequences and alternate-mode-of-operations planning.

Regardless of the life cycle phase to which the analysis is applied (and for which the data is available), there are two basic approaches to failure mode analysis:

- Fault tree analysis--FTA ("top-down" approach)
- Failure mode, effects and criticality analysis--FMECA--("bottom-up" approach)

Each of these approaches is described in the following paragraphs.

Fault Tree Analysis (Top-Down Approach)

The fault tree analysis (FTA) process is a tool that lends itself well to analyzing failure modes found during design, factory test or field data returns. The fault tree analysis procedure can be characterized as an iterative documented process of a systematic nature performed to identify basic faults, determine their causes and effects, and establish their probabilities of occurrence. The approach

involves: First, the structuring of a highly detailed logic diagram that depicts basic faults and hazardous conditions that can lead to system failure and/or user hazard; next, the use of computational techniques to analyze the basic faults and determine failure mode probabilities; and finally, the formulation of corrective suggestions that when implemented would eliminate (or minimize) those faults considered critical.

This procedure can be applied at any time during a product's life cycle. However, it is considered most effective when applied:

(a) during preliminary design, on the basis of design information and a laboratory or engineering test model,

(b) after final design, prior to full scale production, on the basis of manufacturing drawings and an initial production model.

The first analysis is performed to identify failure modes and formulate general corrective suggestions (primarily in the design area). The second analysis is performed to show that the system, as manufactured, is acceptable with respect to reliability and safety. Corrective actions or measures, if any, resulting from the second analysis would emphasize controls and procedural actions that can be implemented with respect to the "as manufactured" design configuration.

The outputs of the analysis include:

(a) A detailed logic diagram that depicts all basic faults and conditions that must occur to result in the hazardous condition(s) under study.

(b) A probability of occurrence numeric for each hazardous condition under study.

(c) A detailed fault matrix that provides a tabulation of all basic faults, their occurrence probabilities and criticalities, and the suggested change or corrective measures involving circuit design, component part selection, inspection, quality control, etc., which, if implemented, would eliminate or minimize the hazardous effect of each basic fault.

The steps, and some of the factors associated with each step that must be considered during the analysis, are shown in Figure 4-27. The following paragraphs discuss each of the steps in further detail.

Step 1 Fault Tree Diagraming

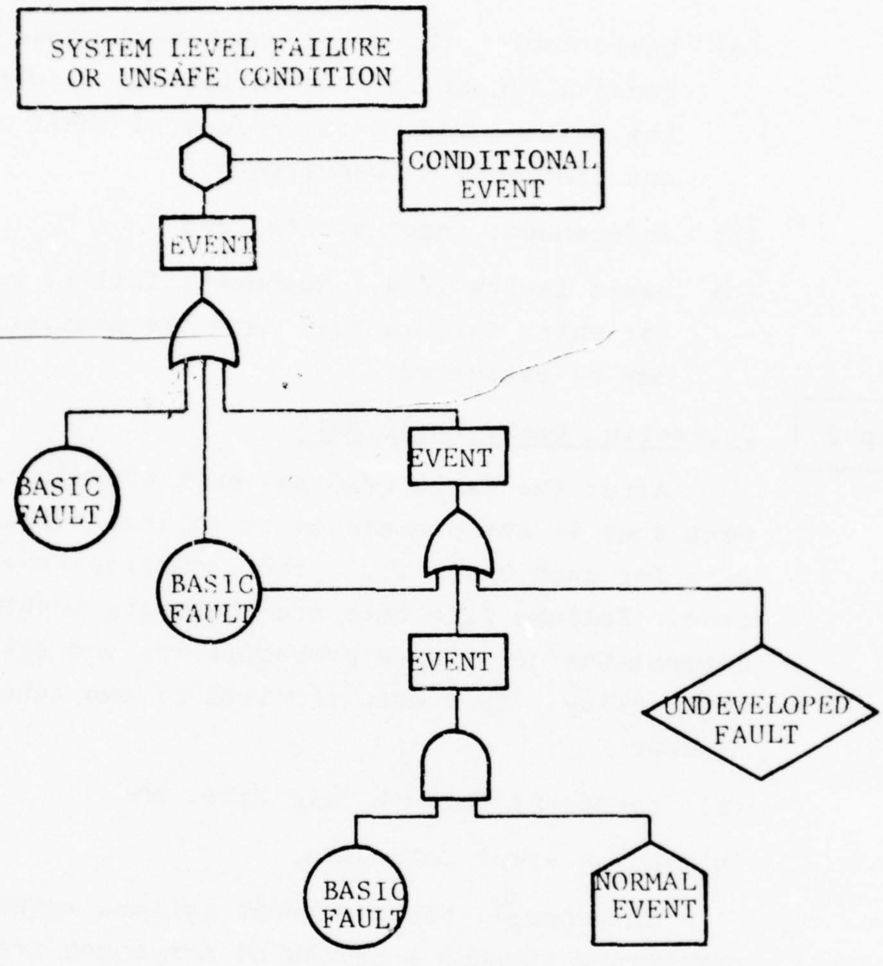
The first step in the fault tree analysis is to develop a detailed logic diagram that portrays the combination of events that may lead to the condition under study. All events (i.e., component faults, human errors, operating conditions, etc.) that must occur to result in the defined fault condition are interconnected systematically through basic logic elements ("and" gate, "or" gate, etc.) to form the fault tree. The fault tree symbols and a representative logic configuration are shown in Figure 4-28.

It is necessary to have a knowledge of the system design, its functional operation and maintenance requirements, and of how the product is used. Then the fault tree is developed, beginning with the defined failure condition and proceeding downward with a series of engineering judgments to define the basic input events. This logic structuring process continues until each input event chain has been terminated in terms of a basic fault. When the fault tree structure is complete, the undesired event is completely defined in terms of:

PROCESS STEPS	FACTORS	
FAULT TREE DIAGRAMMING	• Operating Modes • Performance Levels • Quality and Workmanship • Ease of Maintenance • Failure Modes and Effects	• Environmental Resistance • Operating and Maintenance Equipment • Auxiliary and Supporting Equipment • User Characteristics
↓ COLLECTING BASIC FAULT DATA	• Derating (Stress/ Strength) • Component Quality • Application Factors • Component Failure Rates	• Human Performance and Behavior • Human Error Rates
↓ COMPUTING PROBABILITY NUMERICS	• Operating Time • Failure Distribution Functions	• Computer Modeling • Computer Probabilities
↓ DETERMINING CRITICALITIES	• Computer Modeling • Criticality Numerics	• Fault Ranking
↓ FORMULATING CORRECTIVE ACTION RECOMMENDATIONS	• Design • Derating • Component Screening • Redundancy • Environmental Protection • Maintainability	• Component Selection and Specification • Quality Controls • Operating and Maintenance Procedures • Human Factors • Special Safety Instructions

Figure 4-27

STEPS AND FACTORS INVOLVED IN THE APPLICATION OF FAULT TREE ANALYSIS



DESCRIPTION OF SYMBOLS

an event, usually a fault, resulting from the combination of more basic faults and/or conditions and which can be developed further.

a basic fault (usually a specific circuit, component or human (error) which can be assigned a probability of occurrence.

a fault not developed further as to its causes because of lack of information, time, or value in doing so.

and gate - the output event occurs only when all of the input events are present.

or gate - the output event occurs when one or more of the input events are present.

inhibit gate - similar to an and gate, however, used to include application of a conditional event

an event expected to occur in normal operation.

Figure 4-28

FAULT TREE SYMBOLS

(a) basic faults (hardware and human) whose occurrence alone or in combination can result in the defined hazard regardless of their apparent frequency of occurrence,

(b) independent input events, and

(c) basic faults (e.g., component failure modes) for which failure rate data are available or may be estimated.

Step 2

Collecting Basic Fault Data

After the fault tree has been structured, the next step in the process is to collect failure rate data for each basic fault that comprises the fault tree. Failure rate data are necessary inputs for determining occurrence probabilities and assessing criticality. This data consists of two general classes:

(a) component failure rate data, and

(b) human error rate data.

In general, the component failure rates are determined through a review of component items identified as faults on the fault tree. This involves reviewing the failure modes of each basic element which comprises the identified fault and establishing a modal failure rate, based on historical generic part data and available design application information. Standard reliability prediction techniques, as described in Section 4.3.2, can be used to estimate these failure rate numerics.

Human error rates mean the expected rate at which a failure caused by operating or maintenance personnel takes place, whether intentionally or unintentionally. It is very difficult to

obtain an error rate since very little data exist regarding this area. Since a large scale data base is lacking, human error rates can be developed through subjective techniques based on discussions with personnel familiar with the system operation and maintenance environment. These techniques involve detailing each human error depicted on the fault tree into basic task elements. The intent is to define small segments of human performance--where an error rate can be more easily assessed. Assessing the error rate for these individual elements would involve a literature survey, including a review of currently available human error data and/or prior estimation information from personnel familiar with the operational elements. The final error rate numerics must account for the nature of human performance and its sensitivity to learning, fatigue, and other behavioral factors.

Step 3

Computing Probability Numerics

After the fault tree is structured and all fault data collected, the next step in the analysis process is to compute probability numerics. This involves computing the occurrence probabilities for all basic faults, events, and hazardous conditions (top faults) based on the combinatorial properties of the logic elements in the fault tree. The analysis involves repeated applications of basic probability expressions for the fault tree logic gates. Given a fault tree diagram whose basic faults and output events are properly interconnected, the output event probabilities are computed, starting with the lowest levels and continuing to the highest levels in the tree.

Computation:

And Gate

$$\boxed{P(A) = \prod_{i=1}^{n} P(X_i)}$$

Or Gate

$$\boxed{P(A) = 1 - \prod_{i=1}^{n} \left[1 - P(X_i)\right]}$$

where: $P(A)$ = output probability

$P(X_i)$ = probability of the i^{th} input

n = number of inputs

Step 4

Determining Criticalities

After the occurrence probabilities have been computed, the next step in the analysis process is to determine the criticality of each basic fault. Criticality is a measure of the relative seriousness of the effects of each fault. It involves both qualitative engineering evaluation and quantitative analysis, and serves to provide a basis for ranking the faults for corrective action priorities. The object is to assign a criticality numeric to each fault based on its occurrence probability and its contribution to the overall probability for the fault condition under study.

Criticality can be defined quantitatively by the following expression:

$$\boxed{CR = P(X_i)\ P(H|X_i)}$$

where $P(H|X_i)$ is conditional probability of the overall hazardous condition given that the basic fault (X_i) has occurred.

Computerized techniques can be used to determine criticality numerics.

Step 5

Formulating Corrective Action Recommendations

Finally, after all probabilities and criticalities are computed, all data are reviewed and evaluated in order to formulate general corrective suggestions. These suggestions can be related quantitatively to the fault elements and failure modes identified by the fault tree analysis. These suggestions, in general, would involve.

- Areas for redesign,
- Component part selection,
- Design and procurement criteria,
- Maintenance procedures,
- Inspection procedures,
- Quality controls,
- Special safety instructions.

The scope and extent of the suggested corrective measures would depend on the faults identified and their criticality, and should be considered in relation to their effectiveness, practicality, and cost.

A fault matrix is then prepared to aid in the evaluation and the formulation of the specific recommendations. The fault matrix provides a tabulation of the following information for each basic fault:

- Basic fault identification number,
- Basic fault description,

- The failure mode that would lead to the hazardous condition,
- The occurrence probability $P(X_i)$,
- The criticality numerics,
- The recommended corrective action(s) for those faults considered critical involving design, controls, tests, procedures, inspection, etc., that can be implemented in order to eliminate or reduce the hazardous effect.

A procedure showing application of fault tree analysis to a helicopter system is given in Appendix C of this guidebook.

Failure Mode and Effects Analysis (Bottom-Up Approach)

The failure mode and effects analysis approach can be characterized as a systematic method of cataloging failure modes at the component or part level and assessing the consequences at higher levels of assembly. As with fault tree analysis, the failure mode and effects analysis can be performed utilizing either actual failure modes from field data or hypothesized failure modes derived from design analyses, reliability prediction activities and experiences relative to the manner in which components fail. In its most complete form failure modes are identified at the part level which is usually the lowest level of direct concern to the equipment designer. In addition to providing insight into failure cause and effect relationships, the failure mode and effects analysis provides the disciplined method to proceed component-by-component through the system to assess failure consequences. Failure modes are analytically induced into each component, and failure effects are evaluated and noted, including severity and frequency (or probability) of occurrence The first step in the failure mode and effects analysis is

to list all failure modes at the lowest practical level of assembly. For each failure mode listed, the corresponding effect on performance at the next higher level of assembly is determined. The resulting failure effect becomes, in essence, the failure mode that impacts the next higher level. Iteration of this process results in establishing the ultimate effect at the system level. Once the analysis has been performed for all failure modes, it is usually the case that each effect or symptom at the system level is caused by several different failure modes at the lowest level. This relationship to the end effect provides the basis for grouping the lower level failure modes.

Probabilities for the occurrence of the system effect can be calculated, using this approach, based on the probability of occurrence of the lower level failure modes (i.e., modal failure rate times time). Based on these probabilities and a severity factor assigned to the various system effects, a criticality number can be calculated. Criticality numerics provide a method of ranking the system level effects derived previously. Criticality numerics also provide the basis for corrective action priorities, engineering change proposals or field retrofit actions.

A work sheet can be used to aid in the analysis and should provide, as a minimum, the following information for each part in the hardware item under evaluation.

(a) Part--Assembly symbol and part description.

(b) Mode--List the failure modes associated with the part.

(c) Effects and Consequences--This lists the effects and consequences of each part's modal failure in its component or assembly on the system outputs and interfacing points.

(d) Failure Rate--The basic part failure rate derived from prediction studies.

(e) Probability of Occurrence--This will be the numerical probability of occurrence for each failure mode; can be calculated with the following formula:

$$\boxed{Q = \lambda_m t}$$

where: λ_m = modal failure rate adjusted to mission application

t = time of mission.

(f) Corrective Action Recommendation--Provide recommended corrective action (e.g., redesign, redundancy, derating, etc.) for critical (i.e., high occurrence probability) failure modes.

A procedure showing application of failure mode, effects and criticality analysis to a helicopter system is given in Appendix C of this guidebook.

4.3.4.2 Reliability Growth Testing

The purpose of a growth process is to achieve high reliability in field use. High reliability is dependent on the extent to which testing and other product improvement techniques have been used during development to "force-out" design and manufacturing flaws, and on the rigor with which these flaws are analyzed and corrected. A primary objective of growth testing is to provide methods by which hardware reliability development can be dimensioned, disciplined and managed as an integral part of product development. Other objectives of reliability growth testing are to:

- provide a technique for extrapolating current reliability status to some future result,
- provide methods to assess the magnitude of the test-fix-retest effort prior to the start of development, thus allowing trade-off decisions.

Reliability Growth Factors

In order to structure a growth test program for a newly designed system or major component item, a detailed test plan must first be prepared. This plan must describe the test-fix-retest concept and show how it will be applied to the system or component item under development. The plan must incorporate the following:

1. Specified and predicted (inherent) reliabilities and methods for predicting reliability (model, data base, etc.) must be described.

2. Criteria for reliability starting points, i.e., criteria for estimating the reliability of initial production hardware, must be determined.

3. Test, fix, retest conditions, requirements and criteria, as they relate to and impact the reliability growth rates, must be defined.

4. Calendar time efficiency factors, which define the relationship of test time, corrective action time and repair time to calendar time, must be determined.

Figure 4-29 illustrates the relationships of these factors. The circled numbers refer to the four (4) factors listed above.

For many systems (e.g., avionics) the line representing reliability growth is a straight line on a log-log scale. Other methods of graphically depicting reliability growth are used. For example, a linear plot of reliability versus test time is depicted in Figure 4-30. Similarly, reliability growth can be expressed in reciprocal units, that is, the reduction in unreliability can be expressed as a function of time per Figure 4-31.

Each of these factors given previously affects the reliability growth graph significantly as indicated by the following:

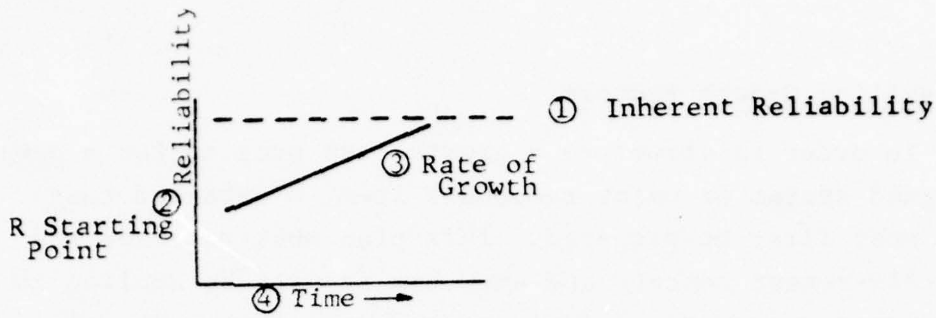


Figure 4-29
RELIABILITY GROWTH PLOT - LOG-LOG SCALE

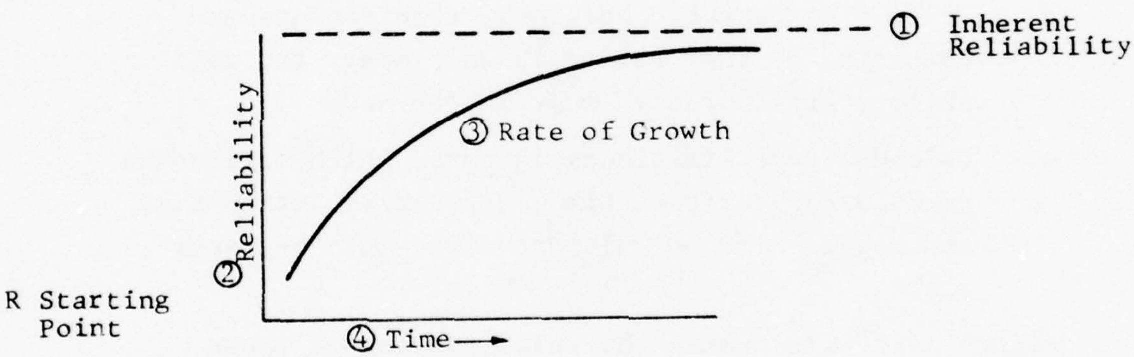


Figure 4-30
RELIABILITY GROWTH PLOT - LINEAR SCALE

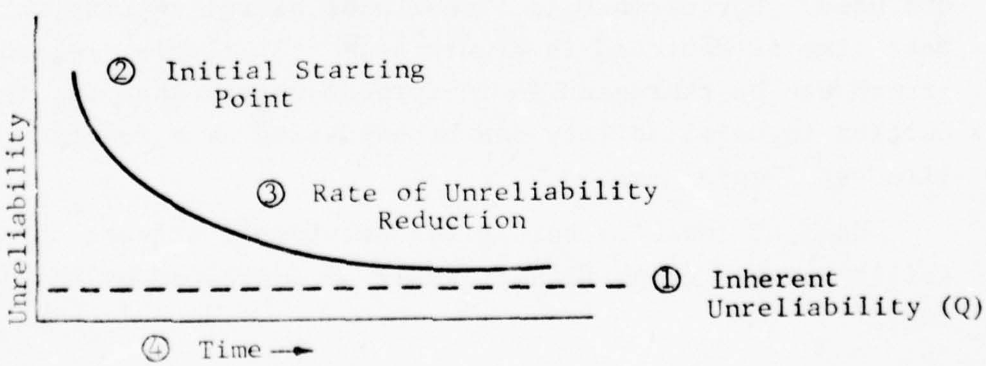


Figure 4-31
RELIABILITY GROWTH PLOT - INVERSE SCALE

1. Inherent reliability--represents the value of reliability established by the design, and which may correspond to the value specified in procurement documents. Ordinarily, the contract specified value of reliability is somewhat less than the inherent value. The relationship of the inherent (or specified) reliability to the starting point greatly influences the total test time.

2. Starting point--represents an initial value of reliability usually within the range of 10-40% of the inherent reliability. Estimates of the starting point can be derived from prior experience or are based on percentages of the estimated inherent reliability. Starting points must take into account the intensity of the R&M design program and the relationship of the system under development to the state-of-the-art. Higher starting points minimize test time.

3. Rate of growth--represented by the slope of the growth curve which is, in turn, influenced by the rigor and efficiency by which failures are discovered, analyzed and by which corrective action is implemented into test hardware. Rigorous test programs which foster the discovery of failures, coupled with management supported analysis and timely corrective action, will result in a faster growth rate and consequently less total test time.

4. Calendar time/test time--represents the efficiency factors associated with the growth test program. Efficiency considerations include repair time, operating/non-operating time as they relate to calendar time. Lengthy delays for failure analysis, implementation of corrective action or short operating periods will extend the growth test period.

Each of the factors listed above impacts the total time (or resources) scheduled to grow reliability to the specified value. Section 5.0 discusses the cost/resource framework relative to growth testing and other product reliability assurance disciplines.

Uses of Reliability Growth Models

Reliability growth models can be used for planning and resource allocation in conjunction with growth test activities. As such, they serve as estimators of the total test time needed to grow to a given reliability value under various levels of corrective action. In this capacity, growth models become valuable management tools providing insight into cost, schedule and test regimen needed to grow reliability to a desired value during development.

A further use of growth models is that of describing the changes in system reliability during a development program. Thus, the actual system reliability growth can be shown in relationship to both contractor and project growth curves. The use of growth curves to depict actual reliability is shown in Figure 4-32. Note that the project growth curve indicates a smaller MTBF value than the contractor growth curve for equivalent test hours. The horizontal dotted line represents 75% of the specified value (at DT II) while the solid horizontal line (340) represents approximately 90% of the specified MTBF.

Reliability Growth Models (Ref. 4-8)

The purpose of most reliability growth models includes one or both of the following:

- Inference from the present system reliability;
- Projection on the system reliability at some future development time.

Most of the reliability growth models considered in the literature assume that a mathematical formula (or curve), as

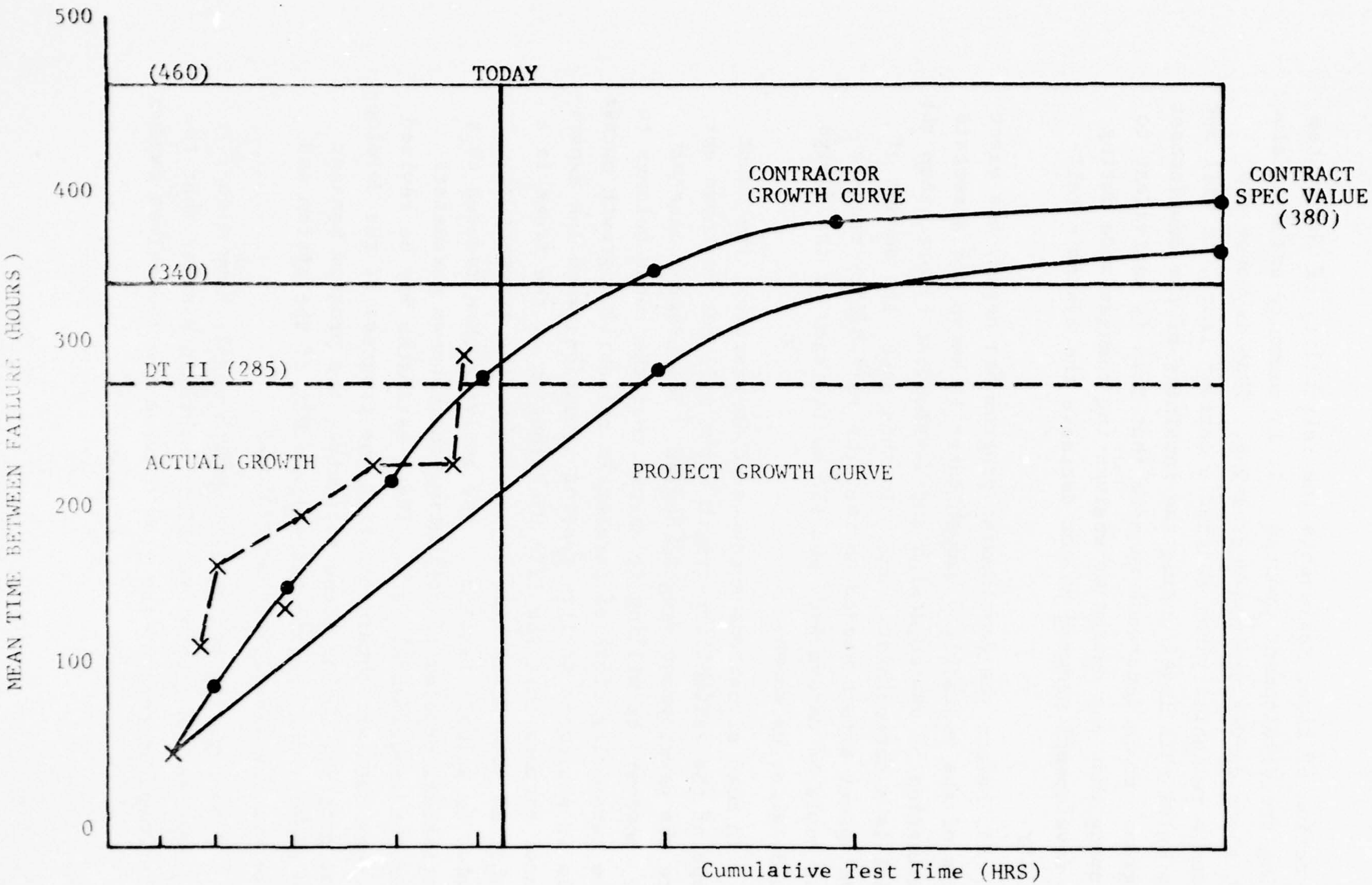


Figure 4-32

XYZ SYSTEM RELIABILITY GROWTH

a function of time, represents the reliability of the system during the development program. It is commonly assumed, also, that these curves are non-decreasing. That is, once the system's reliability has reached a certain level, it will not drop below this level during the remainder of the development program. It is important to note that this is equivalent to assuming that any design or engineering changes made during the development program do not decrease the system's reliability.

If, before the development program has begun, the exact shape of the reliability growth curve is known for a certain combination of system design and development effort, then the model is a deterministic one. In this case, the amount of development effort needed to meet the reliability requirement could be determined, and the sufficiency of the design would, also, be known.

In most situations encountered in practice, the exact shape of the reliability growth curve will not be known before the development program begins. The program manager may, however, be willing to assume that the curve belongs to some particular class of parametric reliability growth curves. This is analogous to life testing situations when the experimenter assumes that the life distribution of the items is a member of some parametric class such as the exponential, gamma, or Weibull families. The analysis then reduces to a statistical problem of estimating the unknown parameters from the experimental data. These estimates may be revised as more data are obtained during the progress of the development program. Using these estimates, the program manager can monitor and project the reliability of the system and make necessary decisions accordingly.

Some Bayesian reliability growth models have also appeared in the literature. This approach assumes that the unknown parameters of the growth curve are themselves random

variables governed by appropriate prior probability distributions. Generally, the form of the prior probability distributions are assumed to be known, and the unknown parameters of the reliability growth curve may be estimated with the aid of Bayes Theorem.

Other models considered in the literature may be classified as nonparametric. This approach allows for the estimation of the present system reliability from experimental data without attempting to fit a particular parametric curve. The estimates are usually conservative and projections on future system reliability are generally not possible. The following models provide a representative cross section of those to be found in the literature:

Model 1. This approach considered a reliability growth model in which the mean time to failure of a system with exponential life distribution is increased by removing the observed failure modes. In particular, it shows that when certain conditions hold, the increase of mean time to failure is approximately at a constant percent per trial. That is, if $\theta(i)$ is the mean time to failure of the system at trial i then $\theta(i)$ may be approximated under certain conditions by

$$\boxed{\theta(i) = A\epsilon^{Ci},}$$

where A and C are parameters. Note that

$$\theta(i+1) = \epsilon^{C}\theta(i).$$

The maximum likelihood estimates of A and C are given.

Model 2. Another model considers a situation where the system failures are classified according to two types. The first type is termed "inherent cause" and the second type is termed "assignable cause". Inherent cause failures reflect the state-of-the art and may occur on any

trial, while assignable cause failures may be eliminated by corrective action, never to appear again. The model assumed that the number of original assignable cause failures is known and that whenever one of these modes contributes a failure, the mode is removed permanently from the system. This approach uses a Markov-chain approach to derive the reliability of the system at the n-th trial when the failure probabilities are known.

Model 3. This model considered the suitability of the Gompertz equation.

$$\boxed{R = ab^{c^t},}$$

$0 < b < 1$, $0 < c < 1$, for reliability growth. In this equation, a is the upper limit approached by the reliability R as the development time $t \to \infty$. The parameters a, b and c are unknown. Techniques for estimates of these parameters are demonstrated by examples showing application of this model.

Model 4. This model considers a deterministic approach to reliability growth modeling. The approach uses data available for several systems in an effort to determine if any systematic changes in reliability improvement occurred during the development programs for these systems. Analysis revealed that for these systems, the cumulative failure rate versus cumulative operating hours fell close to a straight line when plotted on log-log paper. The cumulative failure rate appeared to decrease at approximately the -0.4 or -0.5 power of cumulative operating hours.

The types of systems investigated were of the complex electromechanical nature. The conclusion was that a line with a slope of -0.5 representing cumulative failure rate as a function of cumulative operating

hours on log-log paper would probably be suitable for reflecting reliability growth for similar type systems.

Mathematically, the failure rate equation may be expressed by

$$\boxed{\lambda(T) = KT^{-\alpha}}$$

$K < 0$, $0 \leq \alpha \leq 1$, where $\lambda(T)$ is the cumulative failure rate of the system at operating time T, and K and α are parameters. It follows then that

$$\boxed{\lambda(T) = \frac{E(T)}{T}}$$

where E(T) is the expected number of failures the system will experience during T hours of operation. This yields

$$\boxed{E(T) = KT^{1-\alpha}.}$$

Furthermore, the instantaneous failure rate at T is given by

$$\boxed{\theta(T) = (1-\alpha)KT^{-\alpha}.}$$

For a system with a constant failure rate the mean time between failure (MTBF) of the system at operating time T is

$$\boxed{M(T) = [\theta(T)]^{-1} = [(1-\alpha)K]^{-1}T^{\alpha}.}$$

That is, the change in system MTBF during development is proportional to T^{α}.

With this notation $\alpha = 0.5$ closely represented the types of systems considered.

Model 5. Another model considered a Bayesian reliability growth model for a system undergoing development. The parameters of the model are assumed to be random variables with appropriate prior distribution functions. Using these results, one may project the system reliability to any time after the start of the development program without data and, also, estimate the system reliability after data have been observed. The model further gives precision statements regarding the projection and estimation.

Model 6. This model considers a reliability growth model which assumes that a system is being modified at successive stages of development. At stage i, the system reliability (probability of success) is p_i. The model of reliability growth under which one obtains the maximum likelihood estimates of $p_1, p_2, \ldots, p_k$ assumes that

$$p_1 \leq p_2 \leq \cdots \leq p_K.$$

That is, it is required that the system reliability be not degraded from state to stage of development. No particular mathematical form of growth is imposed on the reliability. In order to obtain a conservative lower confidence bound on p_K, it suffices to require only that

$$\boxed{p_K \geq \max_{i<K} p_i}$$

That is, it is only necessary that the reliability in the latest stage of development be at least as high as that achieved earlier in the development program.

Data consist of x_i, successes in n_i trials in stage i, i=1, ..., K.

Model 7. Another reliability growth model assumed that at stage i of development the distribution of system life length is F_i. The model of reliability growth under which the maximum likelihood estimates of $F_1(t)$, $F_2(t)$, ..., $F_K(t)$ are obtained writing

$$\boxed{\bar{F}_i(t) = 1-F_i(t)}$$

is

$$\boxed{\bar{F}_1(t) \leq \bar{F}_2(t) \leq \cdots \leq \bar{F}_K(t)}$$

for a fixed $t \geq 0$. In order to obtain a conservative upper confidence curve on $F_K(t)$ and thereby, a conservative lower confidence curve on $\bar{F}_K(t)$ for all non-negative values on t, it suffices only to require that

$$\boxed{\bar{F}_K(t) \geq \max_{i < K} \bar{F}_i(t)}$$

for all t _ 0. That is, the probability of system survival beyond any time t in the latest stage of development is at leastas high as that achieved earlier in the development program.

Data consist of independent life length observations

$$X_{i1}, \ldots, X_{in1}, \; i=1, \ldots, K.$$

4.3.4.3 Production and Operations and Maintenance (O&M) Control (Reference 4-10)

Historically it has been noted that the actual field reliability of system hardware is much less than the reliability predicted from procedures such as those previously described. A major factor in evaluating the field R&M is prediction of R&M through a modeling methodology which accounts for degradation factors responsible for the discrepancy between prediction and experience. This methodology must be based on a quantifiable detailed procedure to determine the impact of manufacturing processes and operational and maintenance factors on inherent reliability.

The value of developing a methodology to predict degradation is in using it as an assessment tool to predict improvement in field reliability achievable through production and maintainability controls. The exercise of such controls promotes reliability growth from the degraded field experience level back toward the inherent level predicted from design. The impact of the production, operational and maintenance degradation factors on reliability of a typical helicopter system and the growth achievable from production and maintenance controls is conceptually illustrated in Figure 4-33, derived from concepts presented in Figure 1-2 of Section 1.2.3. The figure depicts the development of a helicopter system as it evolves from initial design, through production and into operational use. The figure shows that an upper limit of reliability is established by design, and that as the helicopter is released to manufacturing its reliability will be degraded and as production progresses, with resultant process improvements and manufacturing learning factors, reliability will grow. The figure further shows that as the helicopter is released to the field, its reliability will again be degraded and as field operations continue, with increasing operational personnel familiarity and maintenance experience, reliability will again grow.

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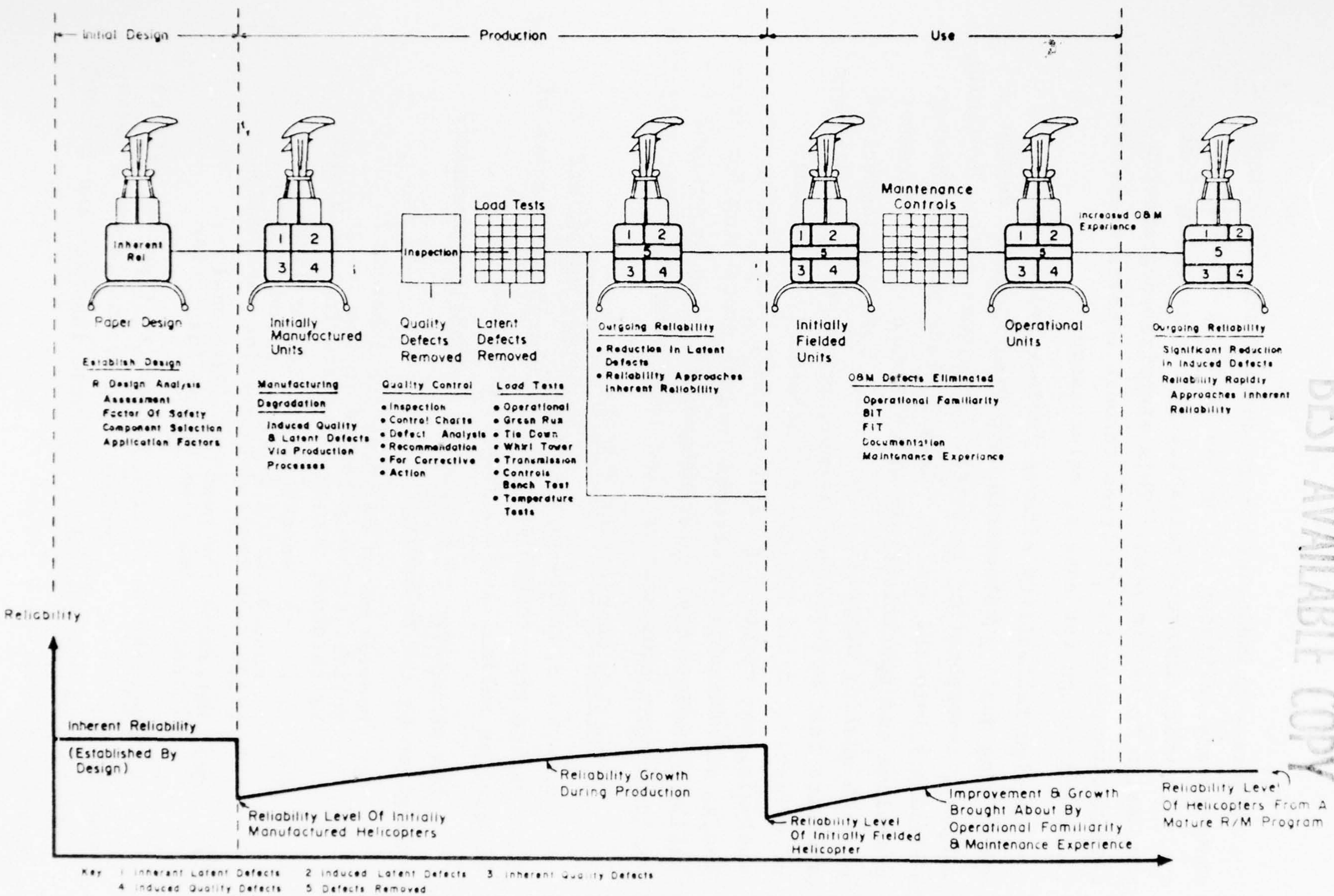


Figure 4-33 IMPACT OF DESIGN AND PRODUCTION ACTIVITIES ON HELICOPTER OUTGOING RELIABILITY

Figure 4-33 indicates that production and maintainability controls are initiated during the hardware development cycle in which inherent reliability is enhanced by forcing the design to be iterated. This minimizes degradation by eliminating potential failures through removal of manufacturing flaws and design for ease of maintenance.

Design reliability efforts include selecting and specifying quality components, applying adequate design margins, incorporating load test techniques and/or designing redundancy into the system. They include both purchasing practices and specifications which insure the procurement of high quality material. They range from development of adequate test methods and assembly processes to development of effective formal systems for accurately reporting, analyzing and correcting failures which occur during use. Design maintainability efforts include processing for accessability, modularity, interchangability, and provisions for built in test equipment on line monitoring and fault isolation.

<u>Production Degradation Factors</u>

Figure 4-33 indicates that reliability may be made to grow during the production process through application of production reliability assurance techniques.

The objectives of production reliability assurance are given by the following:

(a) Provide means by which the inherent reliability as embodied in the design is retained during manufacturing activities.

(b) Assess the contributions to unreliability of manufacturing process, assembly techniques and limited inspection capability.

(c) Determine the need for additional screening tests or better inspection.

As described in Section 1.2.2, two types of defects must be considered -- quality defects and latent defects. These can be further subdivided into inherent and induced quality and latent defects.

To assess the outgoing reliability of a system as it leaves production, values for inherent quality and latent defect rates, induced quality and latent defect rates, and inspection/screening efficiencies must be determined by a process and inspection analysis.

The process and inspection analysis involves: (1) a determination of the induced defects (quality and latent) associated with each of the more significant process steps required in the fabrication of the system as planned -- based on an analysis of planned inspection criteria and historical rejection rates derived from similar processes; (2) an assessment of the total outgoing (from production) defect rate based on the derived process-induced defects and supplied inspection reject rates; and (3) a calculation, based on the ratio of the inherent reliability to the outgoing (from production) reliability. Figure 4-34 depicts this sequence.

The total failure frequency (outgoing reliability) represents the quantity of interest and includes both inherent and quality defects. As previously indicated, these defects are characterized by both inherent (design related) failure factors and induced (process related) failure factors. Figure 4-35 presents a breakdown of these factors as they could apply to helicopter systems, and depicts their relationship to latent defects and quality defects.

In order to show graphically the impact that various inspection and test operations have on defect rates, fault tree diagrams can be prepared. Figure 4-36 shows the relationship between an inherent component failure mode and the inspection operations which occur during the final assembly process of a helicopter. The diagram shows that to experience an outgoing modal failure requires the occurrence of the following four events:

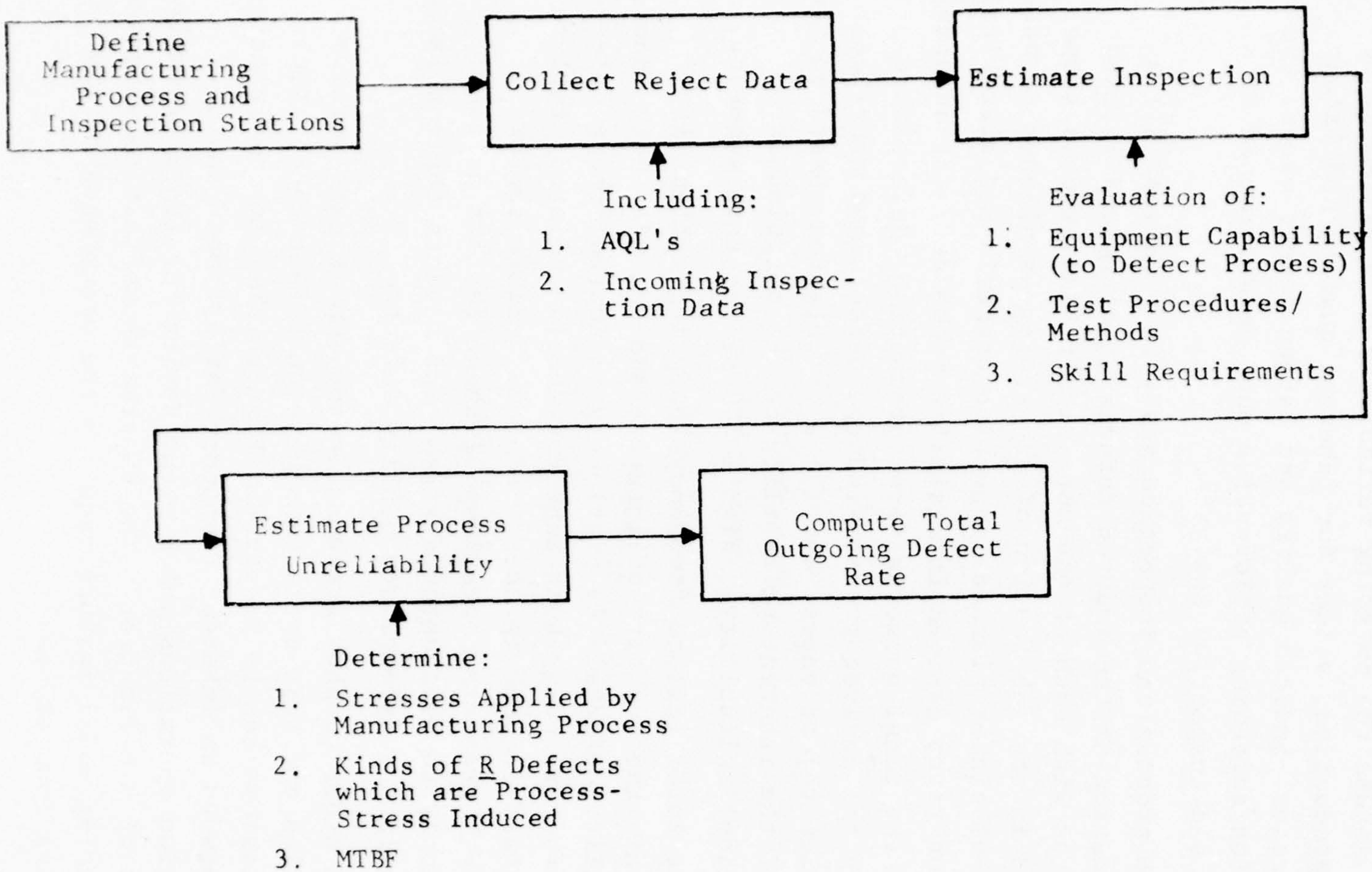


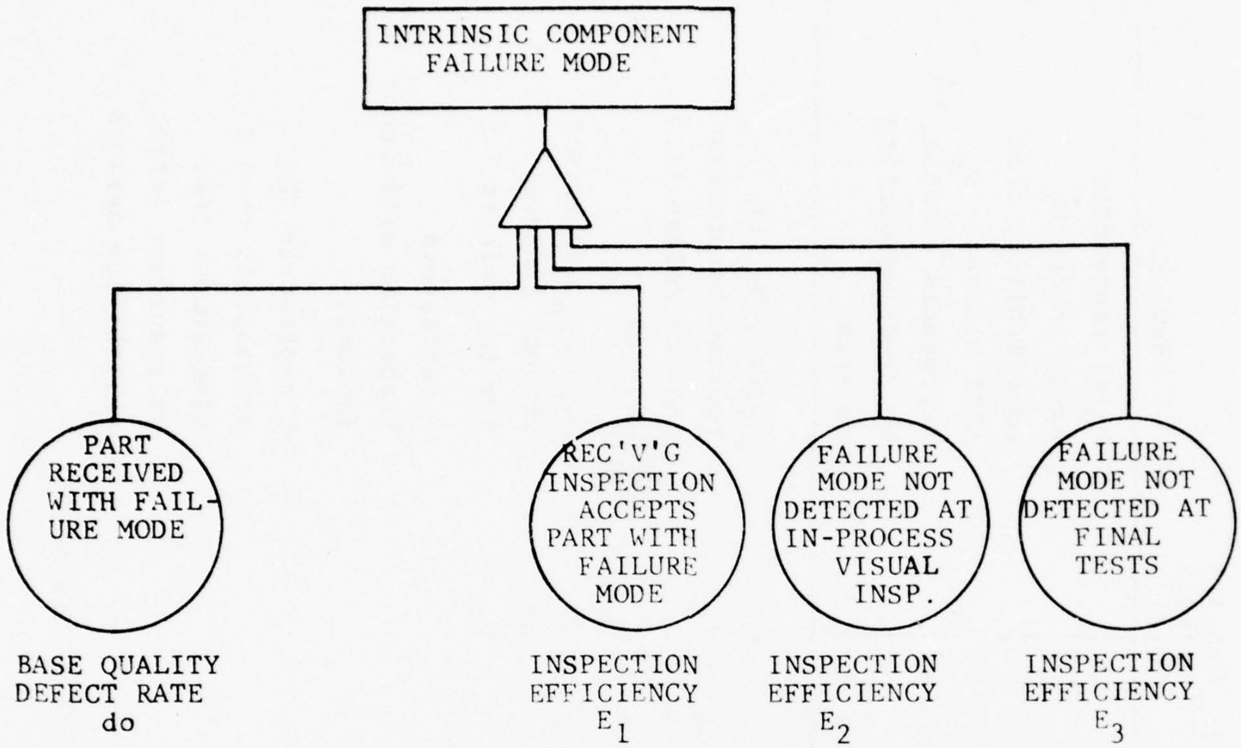
Figure 4-34

FLOW CHART OF ACTIVITIES FOR ESTIMATING PRODUCTION RELIABILITY

		Reliability Defects Q(t)	Quality Defects Q(t)	Remarks
intrinsic (design related)	• component/assembly • selection & specification • procurement policy • stress/strength factors • source inspection • screening criteria • failure analysis	$Q_o(t)$	D_o	$Q_o(t)$ represents basic inherent unreliability from MTBF studies - D_o represents a basic, or received quality defects.
induced (process related)	• receiving inspection	NA	E	$Q_{Ip}(t)$, $Q_{Is}(t)$ represents process induced reliability defects.
	• assembly/fabrication processes	$Q_{Ia}(t)$	D_{Ia}	
	• joining/bonding processes	$Q_{Ij}(t)$	D_{Ij}	
	• in-process inspections	NA	E	D_{Ip}, D_{sp} represents process induced quality defects.
	• final inspection & test	S,E	E	
	(Q.C., tie-down and flight acceptance)	S,E	E	E represents inspection efficiency factors. S represents the probability that a time-stress test will surface latent reliability defects.

Figure 4- 35

Q(t), D FAILURE FACTOR MATRIX



DEPENDS ON

- part selection
- procurement spec and controls
- source inspection
- other experience factors with suppliers

DEPENDS ON

- AQL, sample size, 100% inspection, etc.
- reliability calibration, etc. of test fixtures and equipment
- probability that all component parameters are exercised by test procedures and test equipment
- inspection error
- complexity of inspection or measurement

$$d_{F_i} = d_o\ (1-E_1)\ (1-E_2)\ (1-E_3)$$

where d_{F_i} = the system's defect rate due to this part's failure mode

Figure 4-36

FAULT TREE DIAGRAM FOR INTRINSIC QUALITY DEFECTS

(a) Part received with failure mode,

(b) Receiving inspection accepts part with failure mode,

(c) Failure mode not detected at in-process inspections.

(d) Failure mode not detected at final test stations.

The formula given in Figure 4-36 shows the impact of any one inspection on the outgoing defect rate. For example, with perfect inspection at any one station, E = 1 and $d_{Fi} = 0$.

A key facet of this analysis is the determination of the efficiency of incoming inspection, in-process inspection and final inspection stations. Inspection efficiencies are expressed in percent ranging from 0 to 100%. Perfect error-free inspection is indicated by 100% efficiency.

An inspection may detect (and eliminate) equipment defects by means of either visual inspection, measurements, or combinations of the two. Regardless of the method used, an inspection technique capable of detecting the defect has an associated efficiency factor. Efficiency factors provide a basis for: (1) the fact that no inspection is perfect, and (2) assessment of the ability of that inspection to detect defects.

Efficiency factors are based on a consideration of the following probabilities as they relate to inspection situations:

(a) Probability that all component functions are exercised by the test performed.

(b) Reliability and calibration of test fixtures and equipment.

(c) Probability of inspector error.

(d) Complexity of item inspected.

(e) Inspection instructions, criteria, etc.

Values for process induced defect rates can be derived from an evaluation of reject statistics or can be based on experience factors with similar systems and processes.

The value derived or obtained for reject rates, induced defect rates, and inspection efficiencies can be combined in a process and inspection analysis flow chart which is used to derive a final outgoing defect rate. A simplified flow chart for the final assembly of a helicopter system is shown in Figure 4-37. As previously indicated, the total defect rate or outgoing reliability numeric stemming from a process analysis (Figure 4-37) can then be used to determine manufacturing reliability degradation factors.

Note that a similar flow chart can be prepared for each component in the system. Such charts are particularly useful in identifying manufacturing processes which contribute to component unreliability. Figure 4-38 depicts the simplified process flow chart for fabrication of rotor blades and can be used to estimate the outgoing defect rate for this item.

Production reliability assurance and control should be considered and established throughout development and production phases. A process analysis as described in this section can be performed on helicopter systems and their components during the late development phase on initial production units to establish standardized defect rate statistics and generate inspection efficiency factors. This allows process changes, improved inspection or screening tests, and other improvements in the production area to be made and assessed prior to full-scale production. Similar process analyses should be performed continually during production to assess and control actual outgoing reliability.

A screening program can be formulated based on detailed failure mode studies and formal test and evaluation efforts. For example, such studies with respect to the rotor blade could result in a screening test program that incorporates

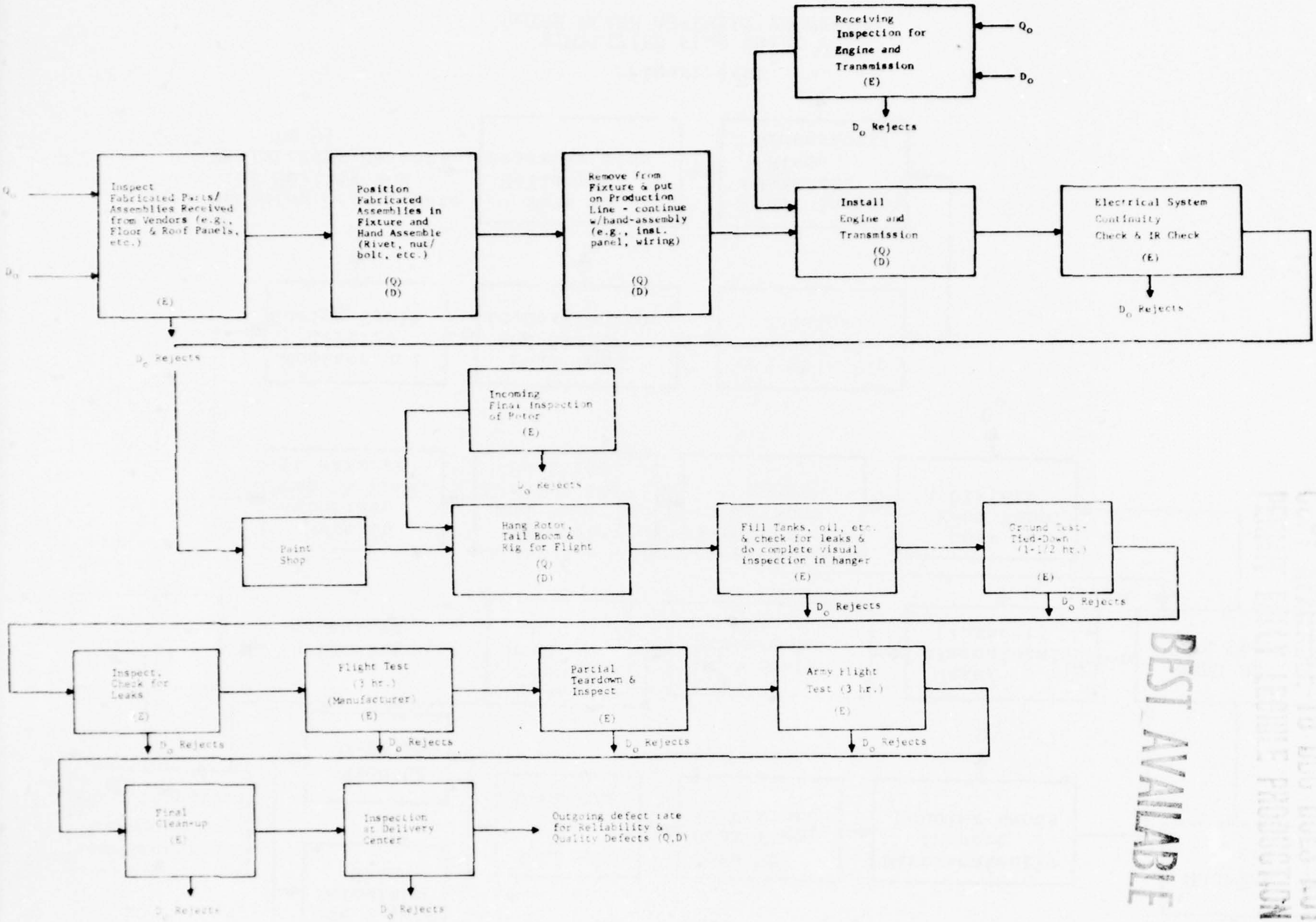


Figure 4-37

SIMPLIFIED FLOW CHART OF HELICOPTER FINAL ASSEMBLY PROCESS

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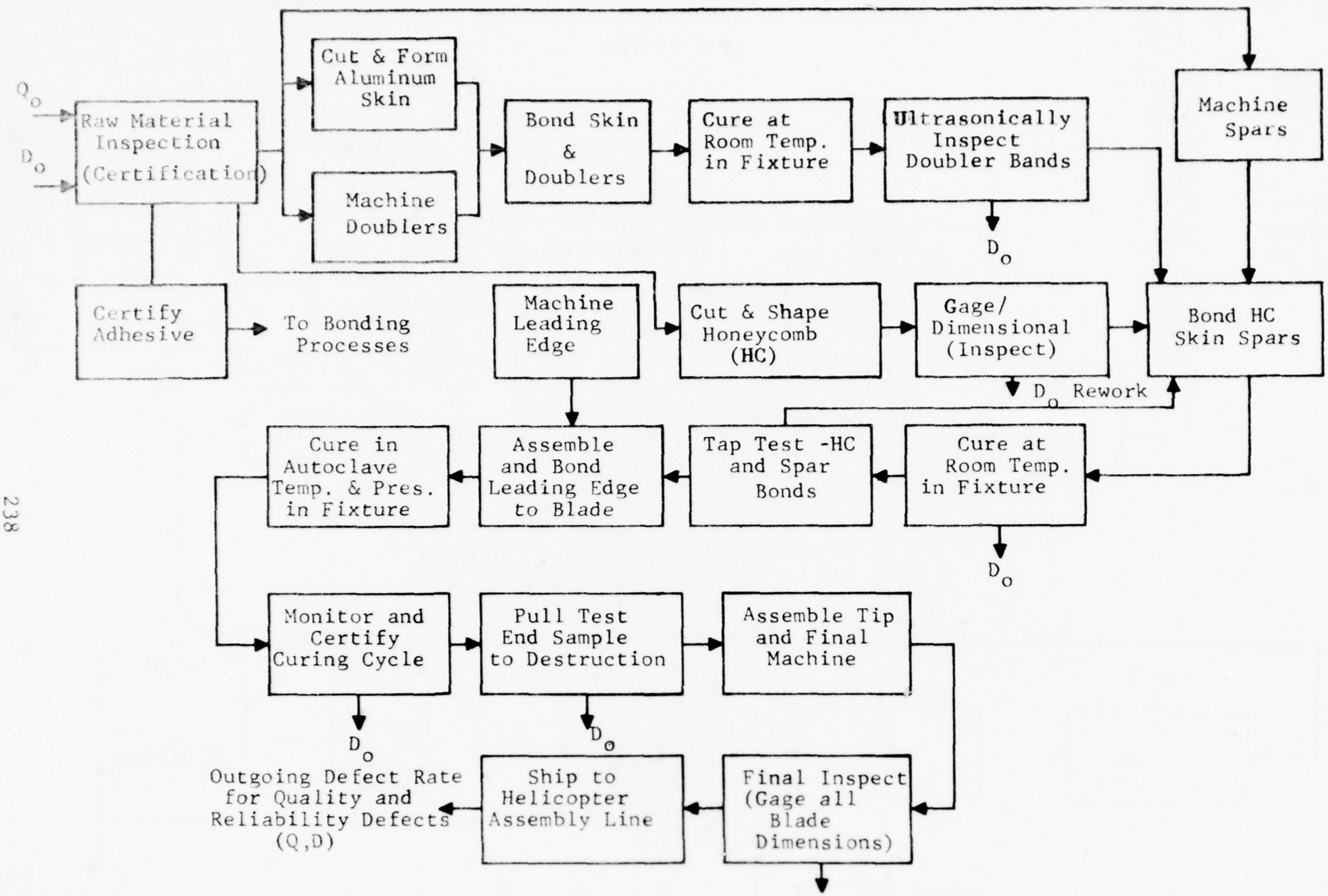

Figure 4-38

SIMPLIFIED FLOW CHART FOR ROTOR BLADE ASSEMBLY PROCESSES

radiography, ultrasonic tests, dynamic vibration, dye penetrant/ultra-violet lamp inspection and tap tests (sound pattern analysis). The helicopter rotor blade failure modes shown in the following table were identified during field and snd factory test programs. Reliability improvement (i.e., possible elimination of certain failure modes) could result from the incorporation of reliability screening tests. Screening test methods are described (which require special inspection procedures or stress elevation techniques) to uncover latent defects.

Failure Mode	Screen
Delamination of Spar to Skin	Spar to Skin bonds are inspected by tap testing to detect unbonded areas. Prior to the tap tests subjecting the blade to a stress cycle would debond marginal interfaces allowing detection.
Delamination of Doublers	Subjecting bonded doublers and skin to low cycle vibrations prior to ultrasonic inspection would expose marginally bonded surfaces.
Tip Weight Fitting Unbonding	Special inspection procedures and instruction on how to detect marginal bonds could reduce incidence of this failure.
Leading Edge to Blade Unbonding	This surface must be 100 percent bonded or blade life is effected. A special test specimen of similar configuration prepared in the same manner as the blade can be cured in the same autoclave. The specimen can then be sectioned to confirm visually bond and pull tested for strength.
Tip Cover Cracking	Penetrant test would uncover surface imperfection that may cause fatigue failures.

The impact of screening tests on outgoing reliability can then be quantified and included in the process and inspection analysis.

OPERATION AND MAINTENANCE DEGRADATION FACTORS

As depicted in Fig. 4-33, reliability is degraded as the helicopter enters the operational phase of the life cycle due to operating and maintenance factors. As time passes in the operational phase, the probability that the user and maintenance personnel will not degrade the inherent reliability of the system increases. The quantification of this factor involves an assessment of the effectiveness of the person during the operation, maintenance, and control of the man/machine system. Efforts to quantify this factor are concerned primarily with:

a) Equipment design characteristics
b) Operating procedures (including maintenance)
c) Work Environment
d) Technical data
e) Communications, logistics and system organization.

To translate these concepts into useful procedures requires the allocation of activities to the man and to the machine, with a complete statement of task elements combined with stimulus conditions which may degrade operator performance.

The basic human elements involved in the operation and maintenance of the system can be viewed as the human counterpart to the basic parts used in the system. In the same manner that reliability prediction involves establishing a failure rate, an error rate for each human element can be established. These error rates then form the basis for establishing the value of the use factor.

An additional factor may be defined to account for reliability degradation occurring due to excessive handling brought about by frequent and poorly executed preventive maintenance actions.

Recent trends in system design have been directed toward reducing the amount of human involvement via BITE and other convenience factors which ease the maintenance burden.

On approach to quantifying this factor is to assess the design for ease of maintenance and, in addition, assess the effects of unskilled or poorly trained maintenance technicians. Techniques are available, as per MIL-HDBK-472, as described in 4.3.3, which quantify, in terms of time factors, the impact of personnel skill and design for ease of maintenance. The formulation of these techniques has been discussed previously. The maintenance time periods to which system maintenance features and personnel skill apply are provided as follows:

- Localization time
- Isolation time
- Disassembly time
- Interchange time
- Reassembly time
- Calibration time
- Checkout time

These periods represent areas in which the amount of human involvement can be reduced, and, consequently, provide the framework for improving the O&M factor. Section 4.4 discusses specific methods for improving ease of maintenance in each of the above time periods.

4.3.4.4 Nondestructive Testing and Evaluation

The growth of reliability toward the inherent level, as discussed in the previous section, was found to rely strongly on the ability to detect and identify defects inherent to basic fabrication materials or induced in the course of manufacturing or field operation and maintenance. Tests to uncover such defects need, for the most part, be performable by average skill level maintenance personnel, not require unrealistic instrumentation and equipment, and not degrade the item being tested.

The scientific discipline of NDT of critical parts or components in helicopters is in a state of development to meet this need. While a number of NDT techniques exist, and a number have been successfully applied (largely under laboratory conditions with scientific supervision). A continuing effort remains for the development of new and improved techniques, particularly for use in the field by lesser skilled personnel.

Though NDT plays a key roll in the identification of manufacturing flaws through detection of inherent defects in raw materials, and subelement and product testing, emphasis in this disucssion will be placed on its application to field maintenance controls. In this context, NDT provides a preventive maintenance tool to detect precursors of failure. NDT techniques in general will provide the basic tool required to promote growth of reliability in the field.

Some of the developed NDT techniques include:

A. Electromagnetic
- Eddycurrent
- Microwave
- Electric Field
- Magnetic Field
- Infrared
- Optical
- Laser
- X-Ray
- Nonlinear Effects
- Voltage and Current Measurements

B. Chemical
- Spectrometric
- Exhaust Analysis
- Oil Analysis
- Olfactronics
- Odor Detection
- Gas Analysis

C. Particulates

- Smoke and Exhaust Particles
- Dye-Penetrants
- Leak Detectors

D. Mechanical

- Acoustical Air Conducted Noise
- Vibrations and Solids
- Ultrasonics
- Bond Testers
- Bearing Testers

E. Nuclear

- Attenuation Measurements
- Backscatter Measurements
- Reaction Measurements or Neutron Activation

Many complete systems or subsystems contain incipient failures which could eventually cause catastrophic failures in the field. While these incipient failures could be detected by complete disassembly and inspection, such procedures are frequently not possible under field conditions. In addition, disassembly, even by skilled service men, often introduces more problmes than are solved. Even more difficulties are faced by the armed services who do not always have available personnel with the necessary skills.

While some existing and often specialized NDT techniques could be employed, there appear to be practical limits as to how far such approaches can be utilized and the utilization of secondary effects for the NDT of operating system and subsystems becomes most beneficial.

Sensing secondary effects (such as acoustical noise, mechanical vibration, visible smoke, or electromagnetic noise) or phenomenon not directly related to the principle functions of the system or subsystem, offers opportunities which will augment, supplement or compliment existing conventional NDT approaches.

The advantage of secondary effects include the following: (1) precursors of failure can be detected without the requirement for disassembly; (2) these precursors can be remotely detected without the need for contacting or built-in sensors; (3) one sensor system can be used for all models, since there are enough common features within major groups of equipments found in helicopters; and (4) the sensor systems are sufficiently simple that they can be used in the field by relatively unskilled personnel.

In the past, special equipment, such as electronic sensing and processing of vibrations, has in some instances been successful in identifying potential bearing failures. Chemical analysis of wear debris in engine oil have been with varying degrees of success, useful in identifying precursors of failure in reciprocating engines. The use of heat and infrared has also proved promising in certain cases.

The following paragraphs describe a technique for detecting incipient failures with the use of secondary effects classification of a nonelectronic system, which could be performed and controlled as part of a field maintenance program.

In order to develop a technique for inspecting and diagnosing equipment, either by direct or secondary effect measurements, it is necessary to understand equipment failure. An excellent source of equipment malfunctions can be found in equipment technical manuals. The maintenance manuals are particularly useful since most of them include "troubleshooting" data.

A representative listing of nonelectronic subsystem malfunctions taken from several maintenance manuals is shown in Figure 4-39. Many of these malfunctions can occur in more than one subsystem. Furthermore, these equipment malfunctions could be classified according to the type of generic failure mechanisms involved.

Figure 4-40 shows a list of generic failure mechanisms that cover most of the failures that occur in nonelectronic equipment. Many of these failure mechanisms can be observed

SUBSYSTEM	MALFUNCTION	
Engine	Internal seizure Incorrect oil Dirty oil filter Defective oil pump Defective fuel pump Improper fuel Water in fuel Dirty fuel filter Loose or restricted fuel lines and fittings Restricted air intake system Dirty air filter	Defective fuel injectors Defective turbocharger Defective turbocharger regulator Fan belt damaged or out of adjustment Defective thermostat Low coolant level Damaged or dirty radiator Defective water pump Cracked manifold Burned or blown manifold gaskets Restricted exhaust system
Electrical	Low battery fluid Bad battery Loose connections Generator defective or out of limits Defective regulator Loose generator drive belt Defective relays	Faulty switches Defective rheostats Defective brushes Faulty thermostats Defective gyro Defective or jammed solenoid Defective ignitor
Hydraulic	Blocked or restricted lines Leaks in fittings Low oil reserve Defective pressure relief valve	Incorrect gas volume in accumulator bottle Clogged or defective filter Defective solenoid valve Defective check valve
Transmission	Defective steer valve body Internal and external oil leaks Low oil level Oil cooler clogged Faulty oil pressure regulator Defective oil pump Incorrect grade of oil Restricted oil lines Defective oil temperature gauge Faulty steer relay valve Piston seal ring leakage Output clutch steal ring leakage	Control linkeage broken or out of adjustment Low oil level Oil cooler clogged Faulty oil pressure regulator Defective oil pump Restricted oil lines Incorrect grade of oil Brakes worn or out of adjustment Faulty clutch selectro valve Excessive vent line pressure Internal binding Reverse range clutch seal ring leakage
Tracks and Suspension	Broken drive shaft Improper track adjustment Work or distorted tracks Defective road wheel bearings Defective shock absorbers Stuck or restricted lockout cylinder piston	Defective idler wheel hub bearings Worn sprockets Air in lockout cylinders Oil leak in lockout cylinders Defective pressure reducer valve
Armament	Defective firing pin Defective sear spring Defective hammer Worn extracter Faulty gas check pad Scored breechlock threads Defective counterbalance assembly Excessive nitrogen pressure in recuperator Low oil in counter recoil systems Worn or defective actuating mechanism	Low nitrogen pressure Defective retracting control valve Defective lines or fittings Scored cannon-mount surfaces Defective recoil cylinder Defective relief valve Worn rifling Jammed or defective breech drive solenoid Ejector worn, defective, or out of adjustment Worn or defective recuperator cylinder seal

Figure 4-39
Representative List of Malfunctions (Reference 4-11)

Mechanical

*Adherence, sticking, seizure	*Leakage
*Looseners, backlash	*Position shift
*Rupture, broken fracture	Creep relaxation
*Fatigue, Brinelling	Deflection misalignment
*Wear, adhesion, abrasion erosion or scoring	Buckling
Vibration	*Heating
*Timing	Shock
Torque	*Slippage
	*Pressure
	Cavitation

Chemical

Corrosion	Contamination
Deterioration	Electrolysis
Change of state, freezing, boiling	Photocatalysis

Electrical

*Deterioration, insulation and contact	*Timing
Electrolysis	Voltage
Current	Demagnitization
*Heating	Photocatalysis
	Depolarization

*Generic Failure Mechanisms

Figure 4-40

GENERIC FAILURE INDICATORS/MECHANISMS

(Reference 4-11)

directly, while some produce other effects which are indications of failure. Also shown in Figure 4-40 is a list of generic failure indicators, one or more of which would be present in most nonelectronic equipment failures

Thirty-five techniques for the detection of generic secondary effects are identified in Figure 4-41. Here, each of the techniques is classified according to the secondary effect utilized, and is assigned a number for identification. Also included is the complimentary failure indicator which is detectable by each technique.

The presence and feasibility of detecting these secondary effects in various nonelectronic subsystems are shown in Figure 4-42. The numbers refer to the specific secondary effect detection technique listed in Figure 4-41. Asterisks in Figure 4-42 identify assemblies and subassemblies which might produce various secondary effects which are not likely to be detectable in the environment. The numbered areas identify assemblies and subassemblies in which failures might be detected.

From the tabulated data in Figure 4-42, it can be seen that each secondary effect technique has significant application as a field detector for failures which could be accomplished during routine maintenance. Two possible exceptions to this observation are visible and electric field--which appear to have limited application. In the case of electric field sensing of secondary effects, the development of high sensitivity E-field sensors could remove this limitation. While both vibration and thermal secondary effect techniques indicate high instances of application, they have the disadvantage that they usually require attached sensors. Exceptions to this would be, for example, the measurement of excessive temperature by an infrared technique, and abnormal vibrations by a remote visable technique.

4.3.5 Maintainability Demonstration

Most typical procurement programs contain requirements for demonstration of a specified maintainability level before a product will be accepted. In such cases, the contractor is obligated

Type No.	Technique	Failure Indicator
1	Infrared	Heating
2	Infrared	Deterioration (contact)
3	Infrared	Current
1	Visible	Timing and Broken
2	Visible	Wear
3	Visible	Leakage
4	Visible	Vibration
1	Magnetic field	Timing
2	Magnetic field	Current
1	Electric field	Voltage
1	Ultrasonic	Leakage
2	Ultrasonic	Fracture
3	Ultrasonic	Deterioration (contact and insulation)
1	Sonic	Leakage
2	Sonic	Wear
3	Sonic	Cavitation
4	Sonic	Deterioration (insulation)
5	Sonic	Flow
1	Vibration	Wear
2	Vibration	Torque
3	Vibration	Sticking
4	Vibration	Bent or broken
1	Thermal	Heating
2	Thermal	Deterioration (contact)
3	Thermal	Slippage
4	Thermal	Sticking, seizure
5	Thermal	Wear
1	Fine particle	Wear
2	Fine particle	Heating
3	Fine particle	Deterioration (contact)
4	Fine particle	Wear
1	Vapors	Leakage
2	Vapors	Heating
3	Vapors	Deterioration (contact)
4	Vapors	Wear

Figure 4-41

GENERIC SECONDARY EFFECT, TECHNIQUES (Reference 4-13)

Note: Numbers refer to type numbers in Table 5-4. Numbers do not rank the techniques.	SECONDARY-EFFECT TECHNIQUES									
Assemblies and Sub Assemblies	Infrared	Visible	Magnetic Field	Electric Field	Ultra-sonic	Sonic	Vibra-tion	Thermal	Fine Particle	Vapor
Internal Combustion Engine										
Filters		3							*	*
Turbocharger	1	1, 4	1		1	1, 2	1, 2, 4	4, 5	4	1
Bearings	1	4			2	2	1, 2	4	1	4
Belt						2	1	*	*	*
Block		3			2					
Camshaft		1, 4	*		*	2	*	*	1	4
Connecting Rods			*		*	2	3, 2	*	2	
Crankshaft	1		*		*	2	1, 2, 3	4	1	4
Fan Blades			1			2	1, 4	*		
Flywheel							*			
Linkages						*	*			
Pistons		1, 4	*	1	1	1, 2	3		1, 4	1, 4
Pulleys	1					*	*	*		
Springs										
Valve Train	*	1, 4	1		1	1, 2	*	*	1, 4	1, 4
Carburetor	3				1	1		*	4	1
Pumps	1, 3	3, 4	1		2	*	3	1	1	1
Reservoir		3								*
Tubing	*	3			1			1		1
Hose		3				5		*		1
Radiator	1	3			*	5		1		1
Thermostat Valve	1					5		1		1
Ducts					1	1		1		
Manifold	1				1	1		1		*
Mufflers	*				1	1				1
Lubricant									1	1, 2
Fuel										
Storage Tank		1, 3								
Tubes		3								
Valves		3								
Gas Turbine										
Bearings	*	4			2	2	1, 2	4	1	4
Blades		1, 2, 4	*		*	2	4	*		
Housing										
Rotors		1, 2, 4	*		*	2	1, 2, 4	*		
Shafts		4			*	2	1, 2, 3, 4	4	1	
Springs										
Manifold						*				*
Pumps		3, 4	*		2	2, 5	*	*	1	1
Fuel Control Unit								*		*
Gears		1, 4	*		*	2	1, 2, 4	4	1	2
Reservoir		3								*
Thrust diverter			*			*	*	*		
Nozzles	1				2			*		
Disc			*		*		1, 2, 4	*		
Tubing		3			*	1, 5				1
Linkages			*			*	*			

* Asterisks identify assemblies and subassemblies which might produce various secondary effects, but where the effect is not likely to be detectable in the environment.

Figure 4-42

NONELECTRONIC SUBSYSTEM/SECONDARY-EFFECT TECHNIQUES MATRIX

(Reference 4-14)

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Note: Numbers refer to type numbers in Table 5-4. Numbers do not rank the techniques.

Assemblies and Sub Assemblies	Infrared	Visible	Magnetic Field	Electric Field	Ultrasonic	Sonic	Vibration	Thermal	Fine Particle	Vapor
	SECONDARY-EFFECT TECHNIQUES									
Power Train										
Bands	1						2	3	1	2, 4
Heat Exchanger	1	3						1		1, 2
Valve		4				5			*	
Axle					*					
Clutch	1	2			*	*	2	3	*	*
Spline					*		1			4
Drive Shaft							1, 4			
Torque Converter		3, 4				2, 5		1, 4	1	2
Transfer Case		3						4		
Universal Joint	1		1			2	1, 2		*	
Bearings	1	4			2	2	1, 2	4	1	2, 4
Gears		1, 4	1		*	2	1, 2, 4	4	1	2, 4
Pump		4	*			2, 5	*		*	
Reservoir		3								1
Controls, Brakes										
Reservoir		3								*
Cable										
Springs										
Actuator									1	*
Drums		1					2	*		4
Pedal and Linkage						*	*			
Shoes	*	1, 2				*	2	3	*	4
Bearings	1				2	2	2	4		
Controls, Directional										
Flight Control Surfaces			1							
Tracks						*	*			
Valves		3				2				
Wheels and Tires						*	4	*	*	
Steering Gear			*			2			*	*
Linkages		2	1			*	*			
Bearings	*				2	2		*		
Structure										
Booms										
Door and Hatches			1			*				
Frames										
Hull										
Occupant Support										
Protective Armor										
Suspension										
A Frame										
Bearings										
Lockout Cylinder			1		1, 2	1, 2, 5	*			1
Air Bearings		4				2, 5				
Shock Absorbers		3				2, 5	3			1
Skids		2								
Springs										
Torsion Bars		2								
Propulsion										
Sprockets		2			*	2	*			
Nozzles	1				*			*		
Propellers and Rotors			1		*	2, 5	*			
Tracks						*				
Water Jets						5	*			
Wheels and Tires						*	4	*	*	*

* Asterisks identify assemblies and subassemblies which might produce various secondary effects, but where the effect is not likely to be detectable in the environment.

Figure 4-42 (Cont'd)

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Note: Numbers refer to type numbers in Table 5-4. Numbers do not rank the techniques. Assemblies and Sub Assemblies	SECONDARY-EFFECT TECHNIQUES									
	Infrared	Visible	Magnetic Field	Electric Field	Ultrasonic	Sonic	Vibration	Thermal	Fine Particle	Vapor
Electrical										
Spark Plugs	1	*	2	1	*	4		*		
Ignitors	1	*	2					*		
Wiring	2		2	*				*	2	2
Switches	2		2	*		*		2	3	*
Solenoids	3	4	1, 2	*		*		*	2	*
Connectors	2							2	3	3, 2
Fuses	3							*		
Gyro	1, 3	4	1, 2		2, 3	2, 4	2	1, 2, 4	1, 2, 3	2, 3, 4
Battery	2		2		*			2		*
Distributor		*	2	1	3	2, 4			*	3
Drive Motors	1, 2, 3	4	1, 2		2, 3	2, 4	1, 2, 4	1, 2, 4	1, 2, 3	2, 3, 4
Generators	1, 2, 3	4	1, 2		2, 3	2, 4	1, 2, 4	1, 2, 4	1, 2, 3	2, 3, 4
Heaters	1, 2		2	*				1, 2		
Ignition Coil			2	1	3	4				
Instruments and Gauges			*	*					2	
Lights	*		*					2	2	
Hydraulic and Pneumatic										
Compressors	1	1, 4	1		1, 2	1, 2	2, 3, 4	4, 5	1	1, 2, 4
Fittings		3			1, 2	1				1
Accummulators		2, 3			1, 2	1				*
Actuators		2, 3, 4	1		1	1, 2, 5	3		1	1
Drive Motors	1	3, 4	1		1, 2	1, 2, 5	1, 2, 4	4	1	1, 4
Filters		3				1			*	*
Fluidic Sensors/Amplifiers		3				1				1
Tubing		3			1, 2	1, 5				1
Valves		3, 4	1		1	1,2,3,5				1
Pumps	*	3, 4	1		*	1, 2, 3	2, 3, 4	4	1	1, 2, 4
Armament										
Firing Pin		4	1			2		*		
Sear Spring			1							
Hammer		4	1			2				
Extractor		4	1			2				
Counter Balance			*							
Recuperator		3, 4	1			2	3			1
Valve		4				2				
Breech Solenoid			*							
Ejector		4	1			2	*			
Barrels and Tube	*		*		2		*	*		
Bore Evacuator			*							
Breech Lock		4	1			2				
Carriage and Trails		2								
Cradle		2								
Elevating & Traversing Mechanisms		2, 4	1			2				
Feed System			*							
Flash Suppressor	*	*				*		*		
Receiver										
Recoil Cylinder		3, 4	1		2	2	1, 3	*		1
Suspension										
Utility										
Firefighting										*
Heating & Air Conditioning	*	4			1	1, 2	*	1		
Passenger Restraint and Comfort										
Ventilating		4			1	1, 2	*	1		

* Asterisks identify assemblies and subassemblies which might produce various secondary effects, but where the effect is not likely to be detectable in the environment. 5/21

Figure 4-42 (Cont'd)

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to demonstrate to the customer that his equipment meets the initally specified maintainability requirements. MIL-STD-471 is intended for demonstrating mantainability at any level (system, subsystem, equipment, etc.) and at any level of maintenance under any defined set of maintenance conditions. The procedure given here for maintainability demonstration is based on that given in MIL-STD-471.

In selecting or designing a maintainability demonstration procedure, the minimum steps that shall be considered are:

a) A check list of qualitative features which are not statistically measurable. These will fall into categories of characteristics applied or characteristics omitted.

b) A list of tasks that are statistically measurable that will be evaluated by the procedures that follow.

The method used for selecting the tasks and the methods for evaluating the tasks are presented below.

Task Selection

A stratification method for selecting the corrective and preventive maintenance task to be used in demonstration testing is given in MIL-STD-471. The method is applicable when failure simulation is used. A discussion of the method is given below.

The corrective maintenance tasks used in demonstration consitutes a representative sample of the total population of corrective maintenance tasks. The steps used in selecting the corrective maintenance tasks are given below.

Step 1. List and categorize all items (parts, modules, assemblies, etc.) in the hardware being demonstrated in accordance with the maintenance concpet employed and the level of maintenance to be demonstrated.

Step 2. Determine the failures/item/1000 hours (cycles, loadings, etc., as applicable) for each replaceable item, using reliability techniques and approved data sources.

Step 3. Determine the total failures per 1000 hrs for each item.

Step 4. Determine the percent contribution of each item to the total corrective maintenance tasks, dividing the item failure/1000 hours by the sum of all the item failures/1000 hours.

Step 5. Group together items within the same category for which the percent contribution is less than 2 percent and assign a percent contribution equal to the sum of the individual percent contribution for these items.

Step 6. Apportion the number of corrective maintenance tasks to be demonstrated in proportion to the item percent contribution to the total maintenance tasks. A minimum of one item shall be apportioned to each category. Specific tasks to be demonstrated are selected by the procuring activity and is accomplished by random selection of categories and random selection of items within a category or type to which percentages have been allocated.

Figure 4-43 is a typical example of a corrective maintenance sample selection. Columns A-F correspond to steps 1-6 given above.

A similar procedure is outlined in MIL-STD-471 for selecting the preventive maintenance tasks. Due to the similarity of the two procedures, the preventive maintenance procedure is not included here.

Test Methods

Six test methods are presented in MIL-STD-471 for maintainability demonstration. The test method used shall be the one best suited to a given situation as decided from considerations of risk, cost, time and on the assumptions associated with each test. A summary of the six methods is presented in Fig. 4-44. A more general discussion is presented below.

Method 1

This method employs two sequential test plans to demonstrate achievement of $\bar{M}_{ct}$ and $M_{max_{ct}}$.

Corrective Maintenance Sample Selection

A	B	C	D	E	F
Item	Failures/item/ 1000 hrs (λ_i)	Quantity of each item (n_i)	Failures per 1000 hours (λ_i)(n_i)	Item Percent Contribution To Total Maintenance Tasks	Column E Regrouped
Category I					
Gears					
Spur	.0001	10	.001	.05	
Worm	.0001	3	.0003	.02	.09
Helical	.0003	1	.0003	.02	
Category II					
Clutch Facing					
Type A	.023	3	.069	3.68	3.68
Type B	.033	2	.066	3.52	3.52
Type C	.005	40	.200	10.70	10.70
Category III					
Module Type (Flip-Flop)	.0057	25	.1425	7.59	7.59
Module Type (Audio-Amplifier)	.0082	30	.2460	13.10	13.10
Category IV					
Resistors	.0002	2000	.400	21.30	21.30
Capacitors	.0001	500	.050	2.66	2.66
Transistors	.0007	1000	.700	37.30	37.30
			1.8751		

Figure 4-43

CORRECTIVE MAINTENANCE SAMPLE SELECTION

Test Method	Specification Requirement	Conditions of Use	Quantitative Requirements
1	$\bar{M}_{ct}, M_{max_{ct}}$	Underlying distribution of corrective maintenance task times in log-normal. Consumer risk = 10% Producers risk = 16% $10 \leq \bar{M}_{ct} \leq 100$ $\frac{M_{max_{ct}}}{\bar{M}_{ct}} \leq 3.7$ (95%) $\frac{M_{max_{ct}}}{\bar{M}_{ct}} \leq 2.1$ (90%)	Specification of both $\bar{M}_{ct}$ and $M_{max_{ct}}$ and selection of 90% or 95% as the percentile defining $M_{max_{ct}}$.
2	$\bar{M}_{ct}, \bar{M}_{pt}, \bar{M}$ $M_{max_{ct}}$	For demonstrating $\bar{M}_{ct}, \bar{M}_{pt}, \bar{M}$, the procedure is based on the Central Limit Theorem, thus the form of the underlying distribution is irrelevant provided the sample size is adequate. Minimum sample size is 50. For demonstrating $M_{max_{ct}}$ the procedure is valid when the underlying distribution of corrective maintenance task times is log-normal.	At least two indices, a mean and a maximum value, must be specified. For $\bar{M}_{ct}$ or $\bar{M}_{pt}$, or a combination of both, producer risk β for one or both must be specified. For $M_{max_{ct}}$ the percentile point which defines the specified value of $M_{max_{ct}}$ must be specified.
3	M_{ct}	Underlying distribution of corrective maintenance task times is log-normal. Sample size equals 20.	Equipment repair (EXT) must be specified.
4	$M_{max_{ct}}, M_{max_{pt}}$ M_{ct}, M_{pt}	Underlying distribution of Maintenance task times is unknown. Confidence level of 75% or 90%. Sample size of 50 tasks.	At least two indices, a median and a maximum value, must be specified. Either a 75% or 90% confidence level must be specified.
5		Method 5 is a procedure for estimating to a given confidence the percentage of the total population of maintenance tasks which lie between the extreme values observed in the sample.	
6	$\bar{M}_{pt}, M_{max_{pt}}$	All possible tasks are to be performed, thus no allowance be made for underlying distribution.	Quantitative specification of $\bar{M}_{pt}$ and/or $M_{max_{pt}}$ must be specified. When $M_{max_{pt}}$ is of interest, the percentile point defining $M_{max_{pt}}$ must be specified.

Figure 4-44

Maintainability Demonstration Test Methods

The "conditions of use" are given in Fig. 4-44. Quantitative specifications for both $\bar{M}_{ct}$ and $M_{max_{ct}}$ must be given. Three tables are given in MIL-STD-471 for use with these sequential test plans. Figure 4-43 is used to reach an accept or reject decision for $\bar{M}_{ct}$. Figure 4-44 defines the accept/reject regions for $M_{max_{ct}}$ when 90% is used at the percentile defining $M_{max_{ct}}$. The maintenance tasks are performed sequentially, the duration of each being compared to both required $\bar{M}_{ct}$ and $M_{max_{ct}}$ and recorded as greater than or lesser than each of the two values. When one plan provides an accept decision, attention to that plan is discontinued. The second plan shall continue until a decision is reached. The equipment is rejected when a decision to reject on either plan has occurred regardless of the status of the other plan. The equipment is accepted only when an accept decision has been reached on both plans. If no accept or reject decision has been made after 100 observations, the test is truncated. Accept/reject rules are given in MIL-STD-471 in case of test truncation.

Method 2

This method is applicable to demonstration of the following indices of maintainability: $\bar{M}_{ct}$, $\bar{M}_{pt}$, $\bar{M}$ and $M_{max_{ct}}$. At least two indices, a mean and a maximum value, must be specified. An accept decision for the item under test can be made only when an accept decision is made for both the mean and maximum.

The "conditions for use" are given in Fig. 4-44. Sample tasks are selected in accordance with the procedure previously outlined. The duration of each are recorded and used to compute the appropriate estimates for the indices being demonstrated. For example if $\bar{M}_{ct}$ is one of the indices, the estimate for $\bar{M}_{ct}$, $\bar{M}_{ct}'$, is computed using

$$\bar{M}_{ct}' = \frac{\sum_{i=1}^{N_c} M_{ct_i}}{N_c}$$

N_c = number of tested corrective maintenance tasks

M_{ct_i} = maintenance downtime per corrective maintenance task of the i-th task

The accept/reject value for $\bar{M}_{ct}$ is

$$\bar{M}_{ct}' + \frac{\phi\sigma_{M_{ct}}}{N_c}$$

where

ϕ = A value obtained from the normal distribution table corresponding to the specified level of consumer risk β.

$\sigma_{M_{ct}'}$ = standard deviation of the sample

The accept/reject criteria is then

$$\text{Accept if } \bar{M}_{ct} \text{ (specified)} \geq \bar{M}_{ct}' + \frac{\phi\sigma_{M_{ct}'}}{N_c}$$

$$\text{Reject if } \bar{M}_{ct} \text{ (specified)} < M_{ct}' + \frac{\phi\sigma_{M_{ct}'}}{N_c}$$

Method 3

This method provides for demonstration of maintainability when the requirement is stated in terms of an equipment repair time (ERT) median. Twenty sample tasks are selected according to the procedure previously outlined. The duration of each are recorded and used to compute the following statistics:

$$\log MTTR_G = \frac{\sum_{i=1}^{20} (\log M_{ct_i})}{20}$$

$$S = \sqrt{\frac{\sum_{i=1}^{20} (\log M_{ct_i})^2}{20} - (\log MTTR_G)^2}$$

where

$MTTR_G$ = The measured geometric mean time to repair. It is equivalent to median corrective maintenance downtime, $\tilde{M}_{ct}$ used elsewhere in MIL-STD-471.

S = standard deviation of log $MTTR_G$

The equipment under test will be considered to have met the maintainability requirement (ERT) when the measured geometric MTTR and standard deviation satisfy the following expression:

Accept if $\log MTTR_G \geq \log ERT + .397(S)$

Method 4

This method employs a test of proportion to demonstrate achievement of $\tilde{M}_{ct}$, $\tilde{M}_{pt}$, $M_{max_{ct}}$, and $M_{max_{pt}}$ when the distribution of corrective and preventive maintenance repair times is unknown. At least two indices, a median and a maximum value, must be specified. An accept decision for the item under test can be made only when an accept decision is made for both the median and maximum.

The "conditions for use" are given in Figure 4-44. Fifty sample tasks are selected according to the procedures previously outlined. The duration of each task is compared to the required value(s) of the specified index or indices and recorded as greater than or lesser than each index.

The acceptable tables are given in MIL-STD-471. The first table is for the medians $\tilde{M}_{ct}$ and $\tilde{M}_{pt}$. This table is given in Figure 4-44. A similar table is given for $M_{max_{ct}}$ or $M_{max_{pt}}$.

Acceptance Table for M_{ct} or M_{pt}

Sample Size = 50

Confidence Level	
75%	90%
Acceptance Level	
22	20

Method 5

This method is not a demonstration procedure. It is a nonparametric procedure for estimating to given confidence the percentage of the total population of maintenance tasks which will be included between the maximum and minimum values observed in the sample. For this reason, a discussion of the method is not included here.

Method 6

This method provides for maintainability demonstration when the specified index involves $\bar{M}_{pt}$ and/or $M_{max_{pt}}$ and when all possible preventive maintenance tasks are to be performed.

The "conditions for use" are as specified in Fig. 4-44. All preventive maintenance (PM) task are performed. The total population of PM tasks are defined by properly weighing each task in accordance with relative frequency of occurrence as follows: Select the particular task for which the equipment operating time to task performance is greatest and establish that time as the reference period. Determine the frequency of all other tasks during the reference period. Where the frequence of occurrence of a given task is a fractional number, the frequency shall be set at the nearest integer. The total population of tasks consists of all tasks with each repeated in accordance with its frequency of occurrence during the reference period.

The estimated mean for $\bar{M}_{pt}$ is computed as follows:

$$M_{pt}, \text{ (Estimated)} = \frac{\sum_{i=1}^{k} f_i (M_{pt_i})}{\Sigma f_i}$$

where

f_i = the frequency of occurrence of the i-th task in the reference period

k = the number of different PM tasks

Σf_i = total number of PM tasks in the population

The accept/reject criteria are as follows:

Accept if $\bar{M}_{pt}$ (required) $\geq \bar{M}_{pt}$, (estimated)

Reject if $\bar{M}_{pt}$ (required) $\geq \bar{M}_{pt}$, (estimated)

For $M_{max_{pt}}$ the PM tasks are ranked by magnitude from lowest to highest. The equipment shall be accepted if the magnitude of the task time at the percentile of interest is equal to or less than the required value of $M_{max_{pt}}$.

4.3.6 <u>Failure Analysis</u>

As indicated in Section 3.0, a uniform method of recording and analyzing failures and malfunctions of end item systems and the components thereof which occur during qualification, acceptance, development and in-process testing must be implemented. The method must include failures which occur at contractor facilities as well as other locations such as testing laboratories, Army test facilities, etc.

Implementation of an extensive failure analysis and failure recurrence control program requires reliability analysts, physics of failure specialists, chemists and metallurgists who have years of experience in analysis of aviation systems and components.

Failure analyses must be performed on failed components and material to determine root causes and underlying mechanisms of failure. The results of all failure analysis activity must be documented on forms (see Appendix C) designed for this purpose. Forms will include entries for part identification data, conditions under which failures occurred, operating parameters indicating degradation, references to applicable plans or procedures and complete details leading up to or surrounding the failure incident. The analysis methods used, including test, X-ray, dissection, SEM, chemical analysis, etc., to determine failure causes. These forms should be included as part of the reliability failure analysis reports and should be submitted for each failed item.

A simplified flow chart showing failure analysis activities is given in Figure 4-45. The chart shows the sequence of the events that must take place when a failure during factory test (i.e., in-process and acceptance tests) occurs.

An acceptance test failure can be defined as any deviation from acceptable limits called out in the acceptance test procedure. Quality control is normally responsible for conducting the acceptance test, and reliability is normally responsible for analyzing failures. Upon discovery of a failure, the Q.C. supervisor should stop the test, initiate a failure report, enter the discrepancy in the log and notify the Army and/or their representatives.

A preliminary analysis should be performed, and the acceptance test discontinued pending direction from program management. Based on directions from program management, the acceptance test will either be continued or held up pending failure analysis completion. Where necessary, services of design engineering or outside part vendors shall be used to assist in analysis. Appropriate forms shall be used for reporting the results of analysis.

In-process failures are defined as any deviation of an assembly, module or component from its in-process test procedure. Quality control is normally responsible for conducting in-process test and for troubleshooting discrepancies which arise. In order to remain cognizant of in-process activities and remain aware of significant trends of discrepancies which may affect the inherent reliability, the reliability analyst should monitor screening board reports, summary sheets, in-process discrepancy reports, etc. Based on trends of discrepancies, it may be decided to initiate an investigation to determine the cause of the observed trend.

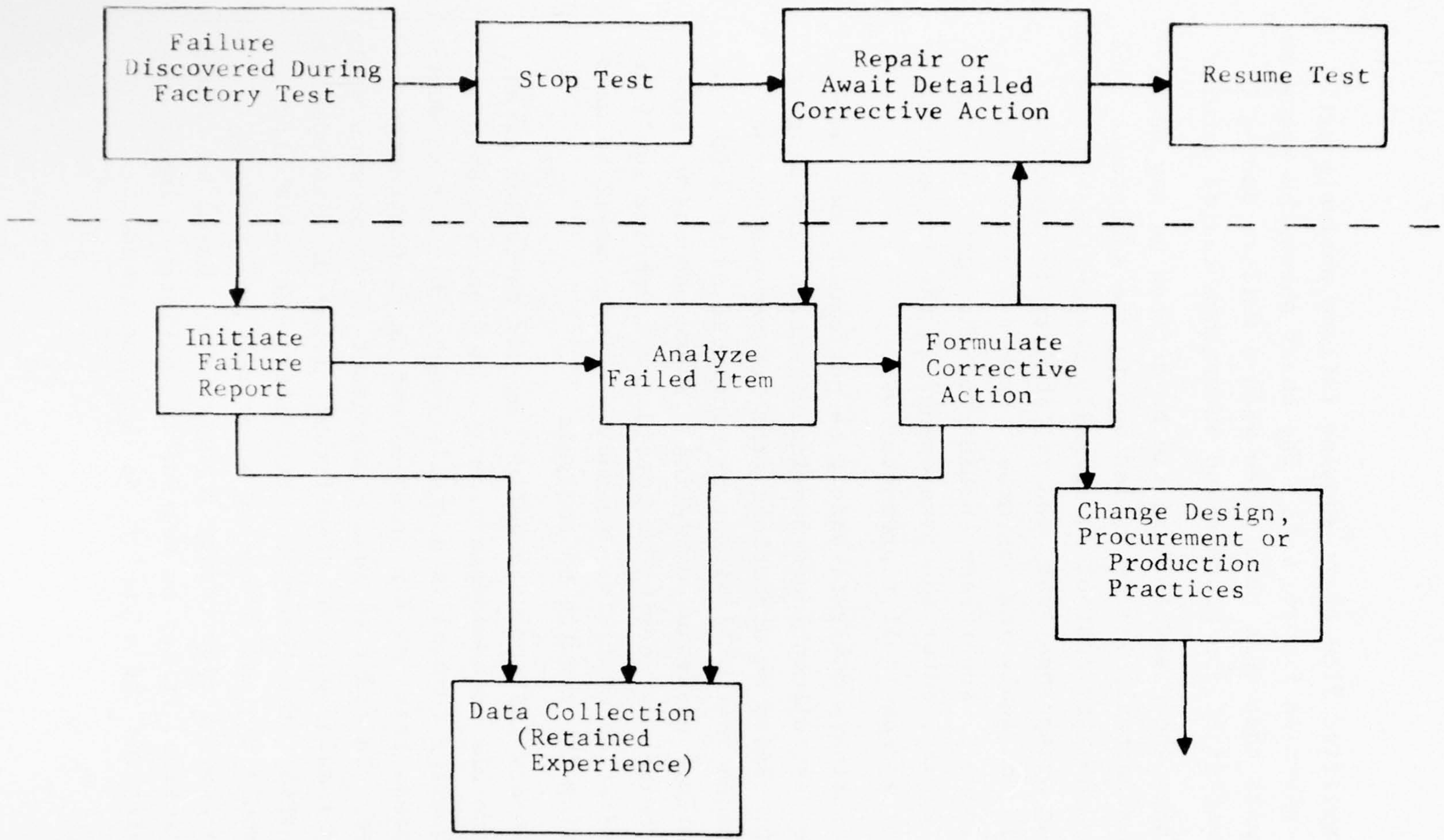

Figure 4-45

SIMPLIFIED FLOW CHART OF FAILURE ANALYSIS ACTIVITIES DURING FACTORY TEST

In addition to acceptance and in-process test failures, all failures occurring during development and demonstration testing shall be analyzed. A development or demonstration test failure is defined as any deviation from acceptable values as called out in the applicable development or qualification test procedure.

Of particular importance are failures which occur during reliability growth testing. Rigorous procedures to detect, analyze and correct failures are necessary during growth test activities.

Upon discovery of a failure, the test operator should initiate a failure report. The reliability analyst should verify the accuracy of symptomatic and causal failure information, especially for failures which occur when the test item is located at outside testing facilities.

As indicated in Section 3.0, corrective measures based on physics-of-failure techniques should be developed and implemented for all failures regardless of their apparent magnitude to eliminate the failure. These measures would involve, as applicable:

- component selection criteria,
- special screening tests to eliminate specific failure mechanisms,
- special inspection and tests,
- special reliability assurance provisions,
- preferred manufacturing practices and controls,
- component stress (strength)
- qualification requirements.

4.4 Reliability and Maintainability Improvement

Previous sections of this guidebook dealt with assessing, controlling and assuring R&M. This section discusses methods to improve and enhance R&M.

An item can be designated and built to have a high MTBF with respect to MTTR. Another alternative, ease of maintenacne, can be designed into the item which would result in short maintenance time elements and a low MTTR with respect to MTBF. Frequently, the most practical way to achieve a high probability of equipment performance is to supplement the design for reliability with a design for efficient and rapid repair and high degree of maintainability. Quantifying these R&M factors provides visibility into the effectiveness of a given aviation system and demonstrates numerically the impact of significant R&M elements including those design, production, operation and maintenance factors depicted in Figure 4-46.

Developing methods to improve R&M from the MTBF and MTTR data is the first step in the analysis process. The next step is to assess the MTBF and MTTR numerics and the observed preventive maintenance downtime data with respect to defined objectives and operating requirements. The intent is to determine quantitatively the extent of improvement considered necessary. Close coordination with cognizant AVSCOM personnel is considered essential at this point in order to assure that improvement goals established are consistent with the overall objectives for the particular aviation system or component. Once quantiative improvement goals are established, the next step is to review the R&M models, their back-up data and preventive maintenance data in detail to identify areas and criteria for improvement and to formulate recommendations that would meet the criteria.

Improving system performance probability and minimizing downtime through reliability (MTBF) action involves a systematic review of several concepts, among which are the following:

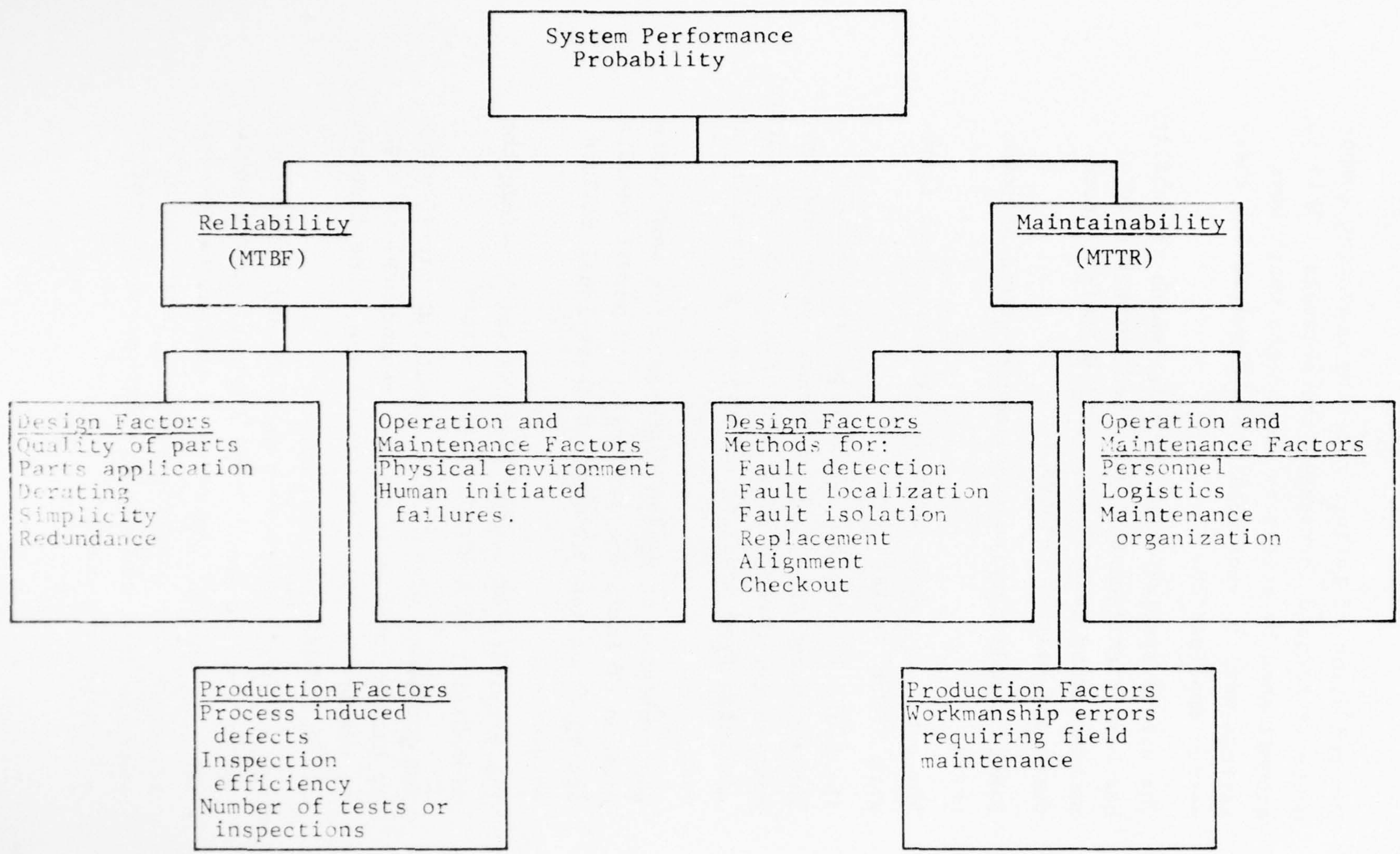

Figure 4-46

FACTORS AFFECTING SYSTEM PERFORMANCE PROBABILITY

- The reduction of failure rates by operating components at reduced (derated) stress levels. This is accomplished by selecting components which have ratings well in excess of those required for their system application.
- The use of special components for which reliability has been significantly increased through special manufacturing techniques, quality control procedures and testing methods.
- Design simplification to eliminate parts or components.
- The substitution of functionally equivalent items with higher reliability.
- The overall reduction of failure rate through increased control of the internal system environment--e.g., through reduction of ambient temperature, isolation from handling effects and protection from dust.
- The provision of design features which enable prediction of incipient failures, and permit remedial action to be taken before an operational failure occurs.
- The provision of design features which reduce the probability of human initiated errors.
- The provision of multiple, identical parts, paths or higher functional levels (redundancy) in order to prevent a system failure in the event that one element fails.
- The reduction of failure rate through increased control of the environment external to the equipment--as through reduction of ambient temperature, isolation from handling effects, isolation of operator from ambient noise and protection of equipment from dust.

- The provision of screening tests for the purpose of significantly reducing incipient failures due to undetected defects in workmanship or components.

Improving system performance probability and downtime through maintainability (MTTR) action involves reducing repair time elements which appear most useful for cost trade off consideration as indicated by the MTTR worksheets. These time elements can involve:

1) Reduction of localization time through increased use of special built-in circuits for fault detection, error warning lights, etc.

2) Reduction of isolation time by:

   - Designing for replacement at higher levels.
   - Utilizing test indications which are less time consuming and/or less difficult to interpret.
   - Designing for minimum diagnostic strategies.
   - Making accessible and obvious both the purpose of the test points and their relationship to the item tested.
   - Improving quality of technical manuals or maintenance aids.
   - Using increased skill level technicians.
   - Increasing depth of penetration of localization features.

3) Reduction of disassembly and reassembly time by:

   - Designing accesses for ease of entry.
   - Reducing number of access barriers.
   - Increasing ruggedness of equipment elements.
   - Reducing need for isolation access by bringing test point, controls and displays out to accessible locations.

4) Reduction of interchange time through an evaluation of its major factors including the following:

- Functional level of replacement (part, component, assembly, unit, etc.)
- Type of replaceable element (e.g., plug-in subassemblies, quick-disconnect units, etc.)
- Number of interconnections per replaceable item.
- Type of connections (hydraulic, fuel, electrical, etc.), insertion and removal forces and special tool requirements.
- Orientation and location of replaceable elements.
- Skill level of maintenance personnel.
- Packaging density.

5) Reduction of alignment time through an evaluation of its major factors including:

- Functional level at which alignment is accomplished.
- Difference between functional levels of replacement and alignment.
- Type and extent of alignment required.
- Number of alignment parameters.
- Accessibility of alignment features and spacing in relation to surrounding elements.
- Skill level of maintenance personnel.
- Alignment sensitivity.
- Difficulty of adjustment criteria.
- Requirement for external test equipment and tools.

- Accuracy, completeness and ease of use of instructions and data

6) Reduction of checkout time through an evaluation of the tasks required to verify that the system has been fully restored to operational capability. Normally, if localization time elements are minimized then the time required for checkout is also minimized.

Computing the impact of the improvement recommendations, which appear most useful for cost tradeoff consideration, on MTBF, MTTR, overall downtime and system performance using the methods and techniques previously described and determining the total cost for their implementation, is the next step in evaluating the effectiveness of the improvement.

Critical to the analysis process is the ability to assess quantitatively the cost effects of reliability and maintainability. The cost of each recommended change must take into account total cost throughout the life-cycle of the system and accordingly must include cost elements associated with design, manufacture, procurement, installation and field use (i.e., operation, maintenance and logistics).

The final activity is to compute cost/benefit factors--develop a numeric for each R and M recommendation which reflects the total cost of the change and its impact on system performance. This will allow the determination of those change recommendations which have maximum cost effectiveness. The recommended changes can then be presented in an improvement plan in decreasing order of cost effectiveness as defined by the computed cost/benefit factors.

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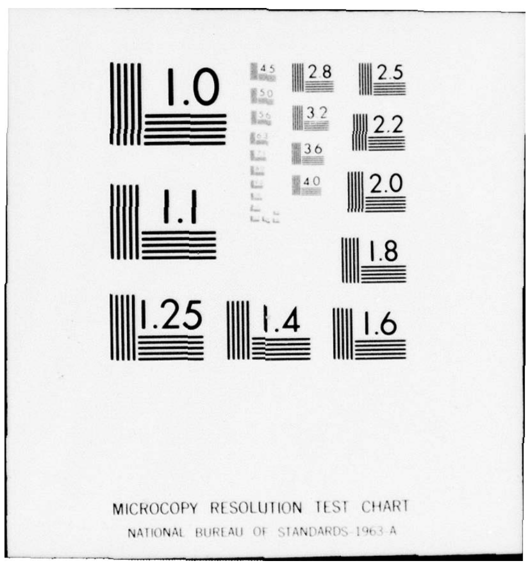
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Section 5.0

COST AND ADMINISTRATIVE CONSIDERATIONS

Section 5.0

COST AND ADMINISTRATIVE CONSIDERATIONS

5.1 General

The preceding sections of this guidebook have described separately the basic provisions and techniques that must be planned and applied during development and other life cycle phases to assess, control and enhance the R&M characteristics of Army aviation system and components. This section discusses: how these R&M elements must be considered in relation to the Army organizational environment and its budgeting constraints, how R&M drives total cost including both acquisition and logistic support costs, and how total cost can be minimized and production cost goals met through effective implementation of these R&M provisions.

5.2 Army Resource Allocation Process

Prior to discussing specific R&M cost factors, it will be useful to review briefly the government's allocation process. This process is illustrated in Figure 5-1. The Army's portion of these funds is broken down in detail in Figure 5-2. Government spending is projected based on a predicted GNP. Past trends and projected pressures (see Figure 5-3) are used to make an allocation for three components of the defense budget

- Manpower Costs,
- O&M Budget, and the
- Procurement Budget.

As a result of this process, DOD is able to project the amount it could afford to spend each year to replace over-age equipment and operational losses, thus retaining a constant size and age force. This allocation process forms the basis for a "design-to-unit-procurement-price" policy for a replacement system. It is the basis for the "design to" philosophy

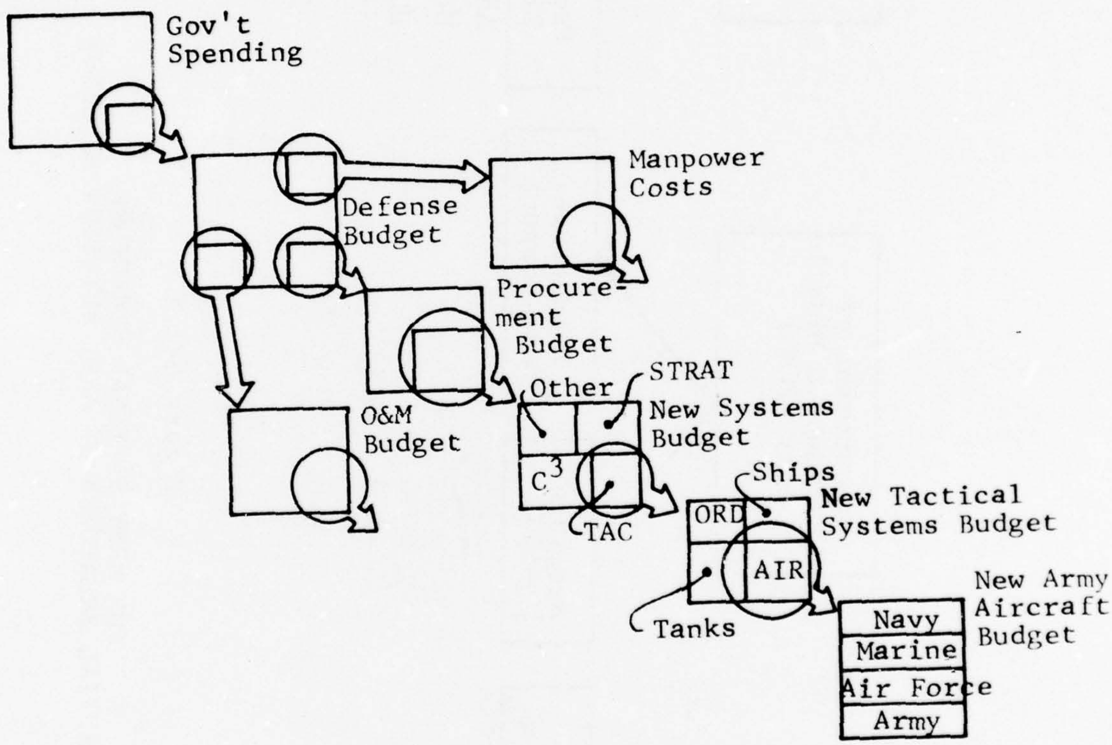

Figure 5-1

METHOD OF DETERMINING "AFFORDABLE" COSTS (Ref. 5-1)

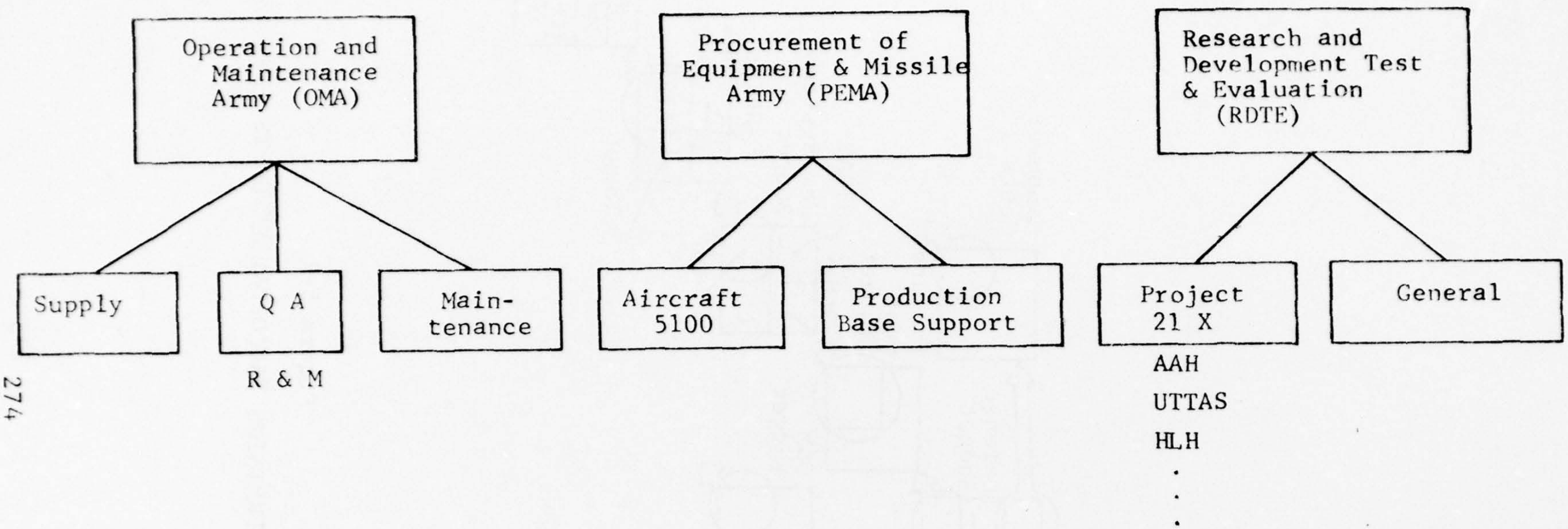

Figure 5-2

THE ARMY'S FISCAL STRUCTURE
(PARTIAL BREAKDOWN OF ARMY AVIATION BUDGETS)

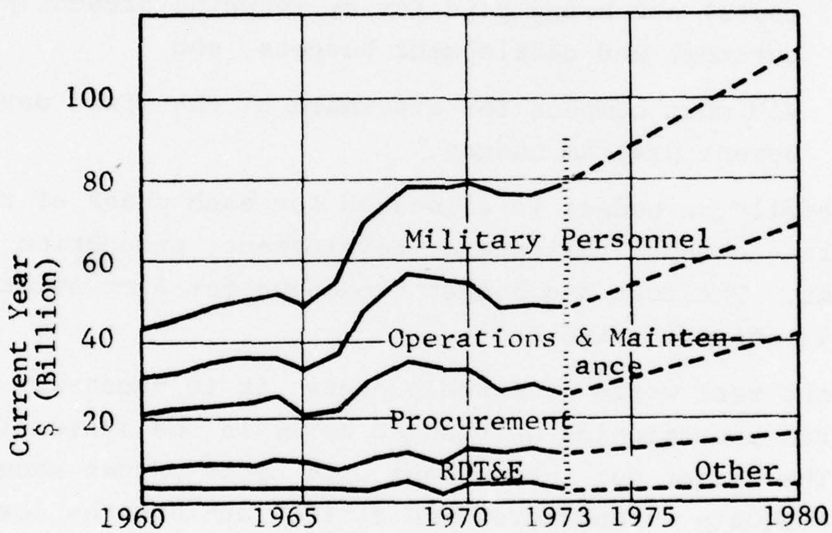

Figure 5-3

DEFENSE EXPENDITURES 1960-1980 (Ref. 5-2)

presently being advocated by DOD. A discussion of the "design to" cost approach and its implication on R&M is discussed in Section 5.4.

The implications of a fixed budget on R&M program provisions are:

1. Past systems with poor reliability and maintainability characteristics (responsible for high O&M costs) are being paid for by reducing present procurement and development budgets, and

2. R&M must compete for its share of the fixed development program budget.

Generally, a budget is allocated for each phase of the life cycle--concept, validation, development, production and deployment. The cost and budget breakdown for Army Aviation systems is shown in figure 5-4.

In the real world of fixed budgets, it is necessary that R&M program provisioning be planned early in the system life cycle. The budget for the various life cycle phases should include adequate expenditures and time to achieve the level of R&M planned for the system. The required R&M must be established based on life cycle cost factors. Life cycle costs include both acquisition and ownership costs and both are significantly impacted by R&M.

Within each phase of the system's life cycle there are alternate strategies for employing R&M resources given a fixed budget. During the development phase, either R&M analysis or R&M testing can be emphasized, reliability growth test time can be increased if demonstration testing is decreased; and reliability can be increased at the expense of system maintainability. During production, additional reliability screening tests can be justified if a decrease in scrap rate is projected at a higher level of assembly. Finally, product improvement proposals can be justified if a reduction in spares provisioning is anticipated. The examples cited above

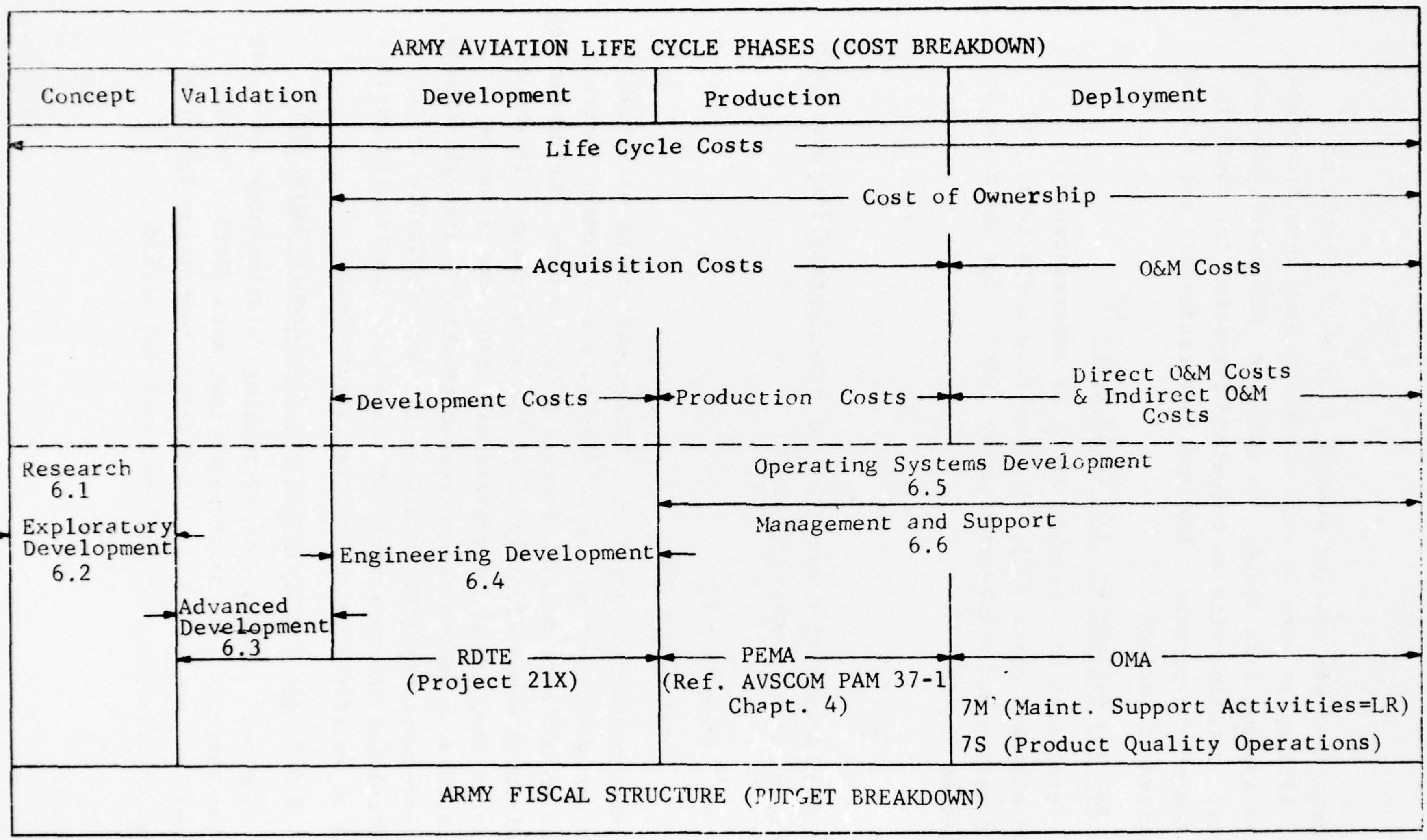

Figure 5-4

COST AND BUDGETS FOR LIFE CYCLE PHASES OF ARMY AVIATION

indicate that R&M must be planned both on the basis of a total life cycle cost as well as within each specific phase of the systems life cycle. In addition, R&M provisions can be cost justified with no budgetary provision for their inclusion of the program. R&M and cost trade-offs are further discussed in Section 5.5.

5.3 R&M and Helicopter Life Cycle Costs

Total cost of ownership (COO) is represented by: 1) development costs (DC), 2) production costs (PC), and 3) operating and maintenance costs (OMC). The above can be stated as follows:

$$COO = DC + PC + OMC$$

The total acquisition cost (AC) of a helicopter includes both development and production costs:

$$AC = DC + PC$$

or $$COO = AC + OMC$$

The unit production costs of a helicopter can be established as a design-to-cost goal specified in a development contract based on DOD's allocation formula. In addition, the"design-to" requirement would normally be an R&M requirement. It should be noted that the above contractual requirements can be achieved at a suboptimal cost-of-ownership. Although minimum cost-of-ownership (COO) would be the most desirable system, difficulties in predicting O&M costs have limited its application as an effective contractual requirement.

5.3.1 R&M and Operating and Maintenance Costs (OMC)

The most complex cost estimating relationships are found in the operating and maintenance cost area (OMC). OMC includes the cost of spares, facilities, technician labor and depot repair--prorated for the total O&M period.

For example OMC can be defined in terms of eight equations as follows:

1. Initial and pipeline spares cost,
2. Replacement spare cost,
3. On-Helicopter maintenance cost,
4. Off-Helicopter maintenance cost,
5. Inventory entry and supply management cost,
6. Support equipment cost,
7. Cost of personnel training and training equipment,
8. Cost of management and technical data.

The factors, elements and terms of these equations identify an incurred cost, time, or expended resource in Army field operations. The initial and pipeline spares cost illustrates the complexity and detail of such a model:

> This cost factor is defined in terms of (a) number of replaceable units in the subsystem, (b) expected peak force flying hours/month, (c) fraction of maintenance actions for which the replaceable units can be repaired in-place, (d) mean flying time between maintenance actions, (e) average depot repair time, (f) fraction of removals returned to depot for repair, (g) expected total force flying hours over life cycle, (h) expected unit cost at the time of initial provisioning, (i) fraction of removals expected to be scrapped.

Similar relationship exists for the other OMC cost factors.

A review of O&M cost factors indicate that they are driven by system R&M characteristics. For example, when considering maintenance costs, the reliability of the helicopter system and its components, in terms of unscheduled maintenance frequencies and MTBF, directly impacts the frequency of

repair and/or overhaul of failed components. Also, the higher the reliability the lower the number of ECP's required and the lower the ECP cost, including fleet retrofit. Significant R&M expenditures during the development phase can be cost justified if improved field R&M performance and lower OMC will result from the R&M efforts.

Budget allocations and projected cost from Ref. 5-3 are plotted in Figures 5-5, 5-6 and 5-7 from two programs: 1) representing nominal programs--level 3, and 2) a high reliability program--level 1 as defined per section 3.3.1 of this guidebook. Note that the crossover point in Figure 5-7 assumes that the system will not (to any appreciable extent) be improved while in the field. Aggressive product improvement programs could reduce O&M costs. The payback in reduced O&M costs would depend on the remaining life of the fleet. In general, R&M improvements made earlier in the system's life cycle will yield greater benefits in reduced O&M costs or costly redesign and retrofit efforts.

Figure 5-8 lists major component failures and the reliability problems that cause the failures. The costs of replacing the components are listed and are based on a 1500 helicopter fleet with a yearly flight schedule of 450,000 hrs. The table is presented to demonstrate the potential benefits that can be derived from high R&M programs. The table does not list the costs required to correct the problem or the effectiveness of the product improvement program. A retrofit of a 1500 helicopter fleet can be costly, but the payoff resulting from the retrofit can be very high. Assuming an effective PIP program could increase MTBF, the following savings can be projected for the fleet:

% Increase in MTBF	10%	20%	30%
Savings in Spares ($/yr)	518,000	946,000	1,313,000

It should be emphasized that the payback in savings from a reliability investment is dependent on the size of the fleet and its projected utilization rate.

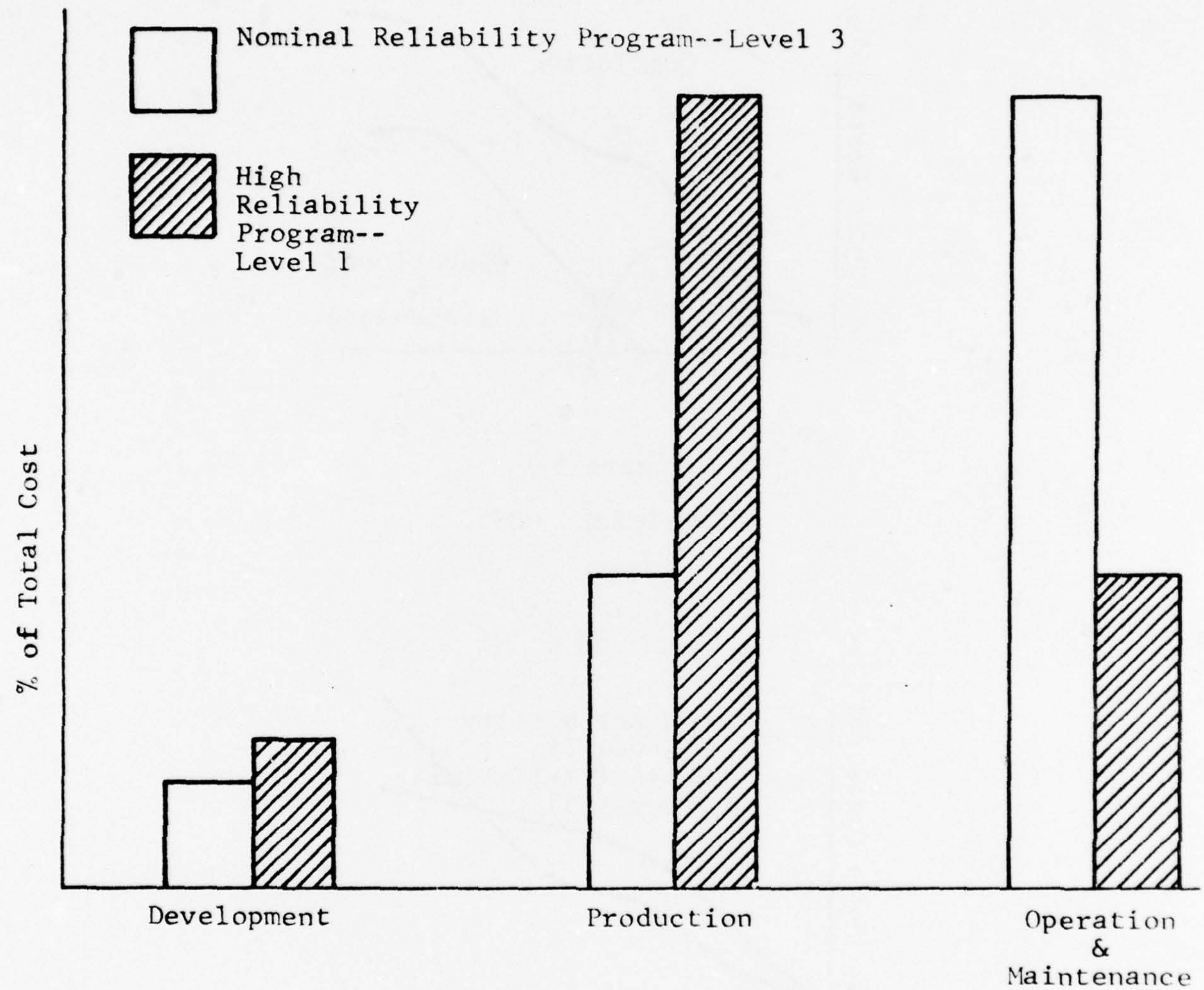

Figure 5-5

COST CATEGORY COMPARISON

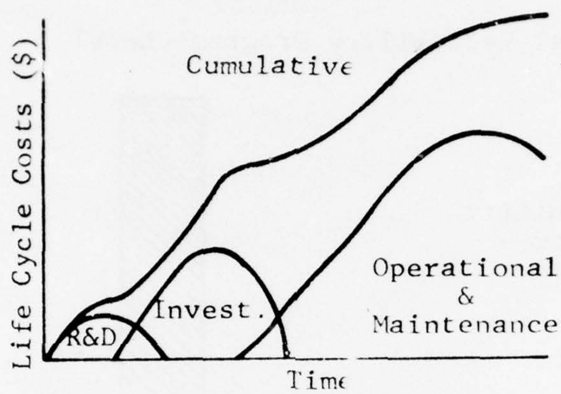

Figure 5-6

TIME-PHASED COSTS

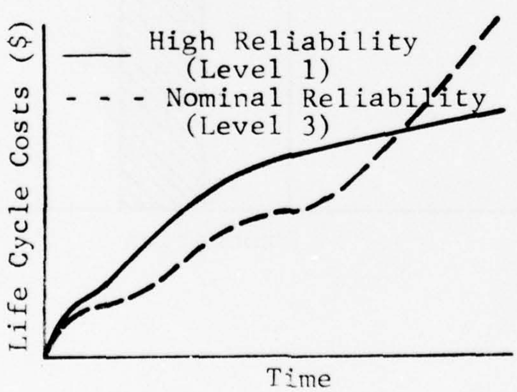

Figure 5-7

TIME-PHASED COST COMPARISON

Part or Assembly	Reliability Problem	MTBR (Replacement) (Flight Hours)	Unit Cost $each	Projected Manpower Costs	Cost 5yrs* Part Cost
(1) Main Rotor Blade	Blade Wear Excessive and Corrosion	141 hrs	$2012	$216,600	$11,026,000
(2) Tail Rotor Gear Box	Leaking, Excessive Wear, Gear Shaft Failure	97 hrs (MTBMA)	$1350	$209,600	$ 5,886,000
(3) Freewheeling Assembly	Leaking and Excessive Wear	198 hrs	$1198	$257,600	$ 4,705,000
(4) Swash Plate and Support Assembly	Excessive Wear and Play in Bearings	160 hrs	$937	$200,403	$ 2,933,000
(5) Receiver Transmitter AN/ARC-114VAF FM	Broken, No Output and Internal Failures	4000 MTBR 409 MTBMA	$3413	$6650	$ 2,567,000
(6) Servo Actuator	Leakage	888 hrs	$887	$99,000	$ 2,208,000
(7) Main Transmission Mast Assembly	Bearing Failures	543 hrs MTBMA	$702	$197,000	$ 2,025,000
(8) Main Driveshaft	Excessive Wear & Leakage	363 MTBMA	$832	$136,000	$ 1,192,000
(9) Starter Generator	Excessive Wear and Sheared	957 hrs	$770	$54,300	$ 1,809,500
(10) Receiver/Transmitter AM	Internal Failures	808 hrs MTBMA	$2783	$2803	$ 1,043,600
(11) Tail Rotor Hub Assembly	Excessive Wear, Bearing Failures Over-Stressed	318 hrs MTBMA	$128	$213,000	$ 813,000

* Based on a 450,000 Flight Hour per Year Flying Schedule and a $9.50/hr Labor Rate.

Figure 5-8

COST OF SPARES FOR A 1500 HELICOPTER FLEET (From Ref 5-4)

As previously discussed, the cost of a retrofit program for 1500 fielded helicopters can be high. Also retrofit costs represent costs incurred now, while the savings resulting from the reliability improvements are generated in the future. Future savings should be discounted to account for the time value of money.

Larger potential reliability benefits at reduced cost can be derived if the reliability program provisioning is included early in the system's life cycle. Reliability testing on ten helicopters in which improvements are made prior to the production effort is less costly than correcting failures in the field.

It is also possible to project cost savings resulting from improved systems maintainability by estimating the cost of maintenance personnel before and after a maintainability improvement is implemented. A procedure for estimating discounted personnel costs is presented in Figure 5-9 (from Ref. 5-2). The present value of personnel maintenance costs are estimated over a four year period.

Figure 5-9 can be used to project savings resulting from maintainability improvement. If a reduced MTTR will allow reduction of maintenance personnel by one man (E5 skill level), the estimated saving can be calculated using the procedure in Figure 5-9 and can be compared with previous costs. The discounted cost of maintenance for the system with improved MTTR is \$204,120. Therefore, the value of the maintainability improvement is

$$\text{VALUE} = \$254,000 - \$204,120 = \$49,880.$$

The above value is just the discounted cost of one E5 level personnel over a four year period. Other maintenance improvements may completely restructure the maintenance manpower requirements. The procedure illustrated in Figure 5-9 would be necessary to estimate the new maintenance costs.

$$COP = \sum_{K=1}^{Y} D_k \sum_{J=1}^{NT} \sum_{S=1}^{NS} (PR_{sjk}) \quad (CP_{sjk}) \qquad Y = 4,\ NT = 2,\ NS = 3$$

YEAR (1,Y)	PERSONNEL TYPE (J=1,NT)	SKILL LEVEL (S=1, NS)	QUANTITY (PR_{sjk})	ANNUAL COST (CP_{sj})	TOTAL $(PR_{sjk})(CP_{sjk})$	TOTAL ANNUAL $\Sigma\Sigma$ (PR)(CP)	DISCOUNT FACTOR D_k	PRESENT VALUE D_k $\Sigma\Sigma$ (PR)(CP)
		E4(1)	0	12,000	0			
1	MIL(1)	E5(2)	2	15,000	30,000			
		E6(3)	1	16,000	16,000			
	CIV(2)	GS12(1)	1	20,000	20,000	66,000	0.954	62,964
		E4(1)	1	12,000	12,000			
2	MIL(1)	E5(2)	2	15,000	30,000			
		E6(2)	1	16,000	16,000			
	CIV(2)	GS12(1)	1	20,000	20,000	78,000	0.867	67,626
		E4(1)	3	12,000	36,000			
3	MIL(1)	E5(2)	2	15,000	30,000			
		E6(3)	1	16,000	16,000			
	CIV(2)	GS12(1)	0	20,000	0	82,000	0.788	64,616
4	MIL(1)	E4(1)	3	12,000	36,000			
		E5(2)	2	15,000	30,000			
		E6(3)	1	16,000	16,000			
	CIV(2)	GS12(1)	0	20,000	0	82,000	0.717	58,794
			21	COP=	$308,000			$254,000

Y = SYSTEM LIFE IN YEARS
NT = NUMBER OF PERSONNEL TYPE (MIL., CIV., CONTRACTOR)
NS = NUMBER OF SKILL TYPES AND SKILL LEVELS

Figure 5-9

COST OF OPERATION AND MAINTENANCE PERSONNEL

5.3.2 R&M and Acquisition Cost (AC)

Acquisition costs include both development (DC) and production costs (PC).

The cost of developing a helicopter system (DC) would include the

- Advanced development of dynamic components,
- Helicopter development program, and
- Demonstration test costs.

Reliability program costs, including reliability growth tests, would be integrated into the development program. Also, all documentation requirements, management and special facilities are included.

The reliability program costs are dependent on the level of system reliability required (defined in Section 3.2.1). Both the number of tests and the test time is influenced by required MTBF. A high system reliability will require more types of tests than a reliability program that concentrates only on flight safety (level 3 program). More tests and/or longer tests will uncover additional problems, permitting corrective action and resulting in higher total reliability.

The types of subsystem and system tests that can be employed in a reliability growth test program include,

- Controls--bench tests,
- Dynamic system test,
- Hub bearing tests,
- Transmission open loop tests,
- Whirl tower tests,
- Tiedown tests,
- Climatic system tests, and
- Flight tests.

All bench tests should be performed using hardware that simulates production units and adequate test time should be scheduled to detect, with a reasonable amount of confidence, all significant failure modes. Figure 5-10 lists recurring and non-recurring costs per test hour for selected reliability growth tests. Costs for two typical helicopters are listed, Type I is a single rotor observation helicopter and Type II is a dual rotor cargo helicopter. Both lead time and estimated test hours per month are listed. The tables can be used to estimate test cost and duration of helicopter components if the required MTBF is established.

One method for estimating test time was recommended in Reference 5-6--the method is known as the 2-MTBF technique. To illustrate the technique an example is presented. Assume the control system on a Type I helicopter is to be designed for an MTBF of 1000 hrs. Using the 2 MTBF technique, 2000 hrs. of testing is planned. The test costs (TC) from Figure 5-10 (line 2) are estimated to be:

$$TC = \$74,000 + (37\ \$/hr)\cdot(2000\ hrs)$$

$$TC = \$148,000$$

Figure 5-10 also indicates a 6 mo. lead time is required to set up the test, and 4 months of calendar time would be required to complete the testing. Down time involved in locating, correcting, and fixing identified failures is not included in the estimate. Other methods are available to predict the test time required to achieve a specified level of reliability. The subject is discussed under reliability growth testing in Section 4.3.3.

A significant portion of reliability growth test costs are non-recurring (e.g., cost of test preparation and test fixtures). The costs shown in Figure 5-10 are plotted as a function of test hours in Figure 5-11. The data indicates that as test hours increase, the per hour cost of the test decreases. Reliability growth testing usually requires

TECHNIQUE	COSTS				SCHEDULES			
	HELICOPTER I		HELICOPTER II		HELICOPTER I		HELICOPTER II	
	Non-recurring ($1000)	Recurring ($/hr)	Non-recurring ($1000)	Recurring ($/hr)	Lead Time (mo)	Oper. Rate (hr/mo)	Lead Time (mo)	Oper. Rate (hr/mo)
RELIABILITY GROWTH TEST								
Controls Bench Back-to-Back	94	41	211	51	6	500	6	500
Controls Bench Single Specimen	74	37	166	46	6	500	6	500
Tiedown	2,300 (mod 2,100)	1,700	-	-	24 (24)	165	-	-
Dynamic Systems Test	2,020	580	-	-	20	200	-	-
Whirl Tower	2,580 (mod 560)	220	6,187	326	20 (20)	350	22	350
Hub Bearing	N/A	N/A	144	49	N/A	N/A	9	400
Transmission Open Loop	2,284 (mod 480)	354	-	-	21 (18)	350	-	-
Tail Rotor Whirl Tower	330	110	N/A	N/A	16	400	N/A	N/A
Alaska Climatic	-	2,500	-	4,630	-	20	-	20
Yuma Climatic	-	2,500	-	4,630	-	20	-	20
Flight	-	2,500	-	4,630	24	70	26	70
DEMONSTRATION TESTS								
Flight (Development Phase)	-	2,500	-	-	N/A	50	-	40
Flight (Operational Phase)	-	200	-	200	N/A	50	-	40

Figure 5-10

SUMMARY OF TEST TECHNIQUE COSTS AND SCHEDULES (Ref. 5-5)

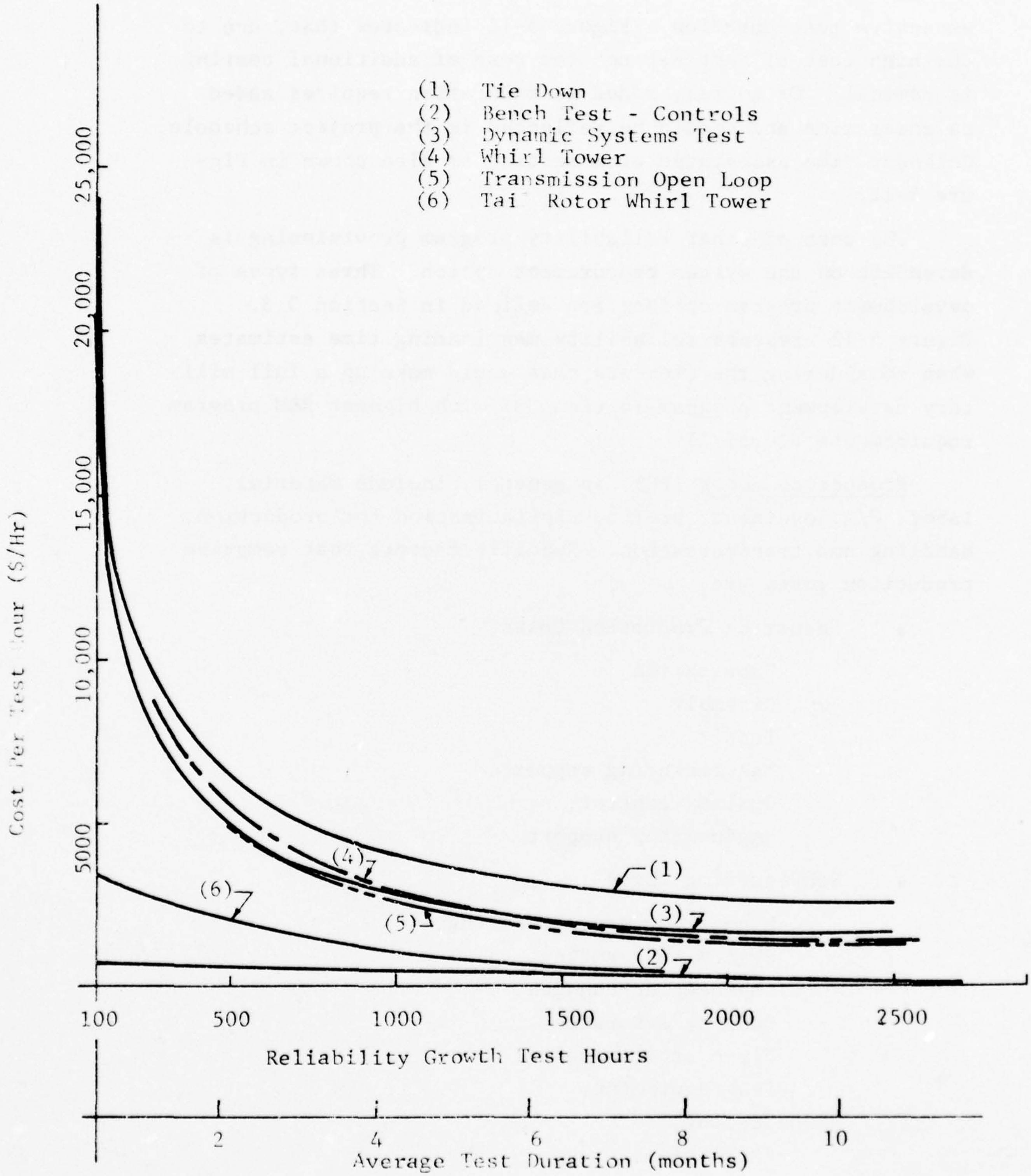

Figure 5-11

RELIABILITY GROWTH TEST COSTS

extensive test duration. Figure 5-11 indicates that, due to the high cost of test set up, the cost of additional testing is nominal. Of course, added test duration requires added calendar time and should be reflected in the project schedule. Calendar time associated with testing is also shown in Figure 5-11.

The cost of other reliability program provisioning is dependent on the system procurement option. Three types of development program options are defined in Section 3.3. Figure 5-12 presents reliability man loading time estimates when considering the elements that would make up a full military development program (option 3B) with highest R&M program requirements (level 1).

Production costs (PC), in general, include material, labor, G/A, overhead, profit, capitalization for production, handling and transportation. Specific factors that comprise production costs are:

- Recurring Production Costs

  Fabrication,
  Assembly,
  Test,
  Manufacturing support,
  Quality control,
  Engineering support.

- Nonrecurring Costs

  Manufacturing engineering,
  System integration,
  Engineering changes,
  Quality assurance,
  First article tests,
  Test equipment,
  Tooling,
  Facilities,
  Documentation.

PROGRAM ELEMENT	EFFORT (MAN-MONTHS)	DURATION (MONTHS)
Management & Control Planning	36	36
R&M Apportionment	4	4
R&M Prediction & Design Analysis	36	18
Maintenance Concept	3	3
Failure Mode Analysis	4	8
Component Control & Standardization	4	12
Design Review	4	As Required
Reliability Growth Testing*	24	18
R&M Demonstration Test*	16	12
Failure Analysis	5	18
Forced Defect Testing*	12	12
Reliability Assessments	8	8
Data Collection & Feedback	6	36

* Monitoring Only

** Based on a 3 year Development Program and where test models are available after 18 months

Figure 5-12

COSTS FOR R&M PROGRAM ELEMENTS

- Program Management

  Planning,
  Administration,
  Control.

Figure 5-13 depicts actual unit production costs of several Army and Navy helicopter systems. The aircraft empty weight is seen to correlate well with cost. The attack helicopter (AH-1G) falls above the trend line, possibly due to the cost of armaments for this helicopter. The general relationship between weight and cost should be a consideration in a design-to-unit production cost effort.

R&M requirements can have a significant impact on production costs. Redundant systems can add to both system weight and cost. High quality components and stringent quality control during production can also increase PC. High strength alloyed steels selected to increase the design safety factors may be costly to machine and may also increase raw material costs. The cost factors associated with production test failures can be minimized if failure modes are eliminated during design, and if reliability defects are uncovered early in the production cycle. The factors that would reduce production costs, as reliability requirements are increased, include: rework, MRB, scrape rate (e.g., blade scrape rate) and QC inspection. In Section 5.4, methods in which reliability provisions can decrease production costs are discussed.

5.4 Design-to-Cost Concepts

Design-to-cost is a concept applicable to the acquisition of defense material. It is presently being proposed to control unit production cost. In effect, the procuring agency establishes an estimate of what the unit production cost should be and, through the request for proposal, announces the production cost to the industrial community. The design-to-unit production cost (DTUPC) is based upon economics or

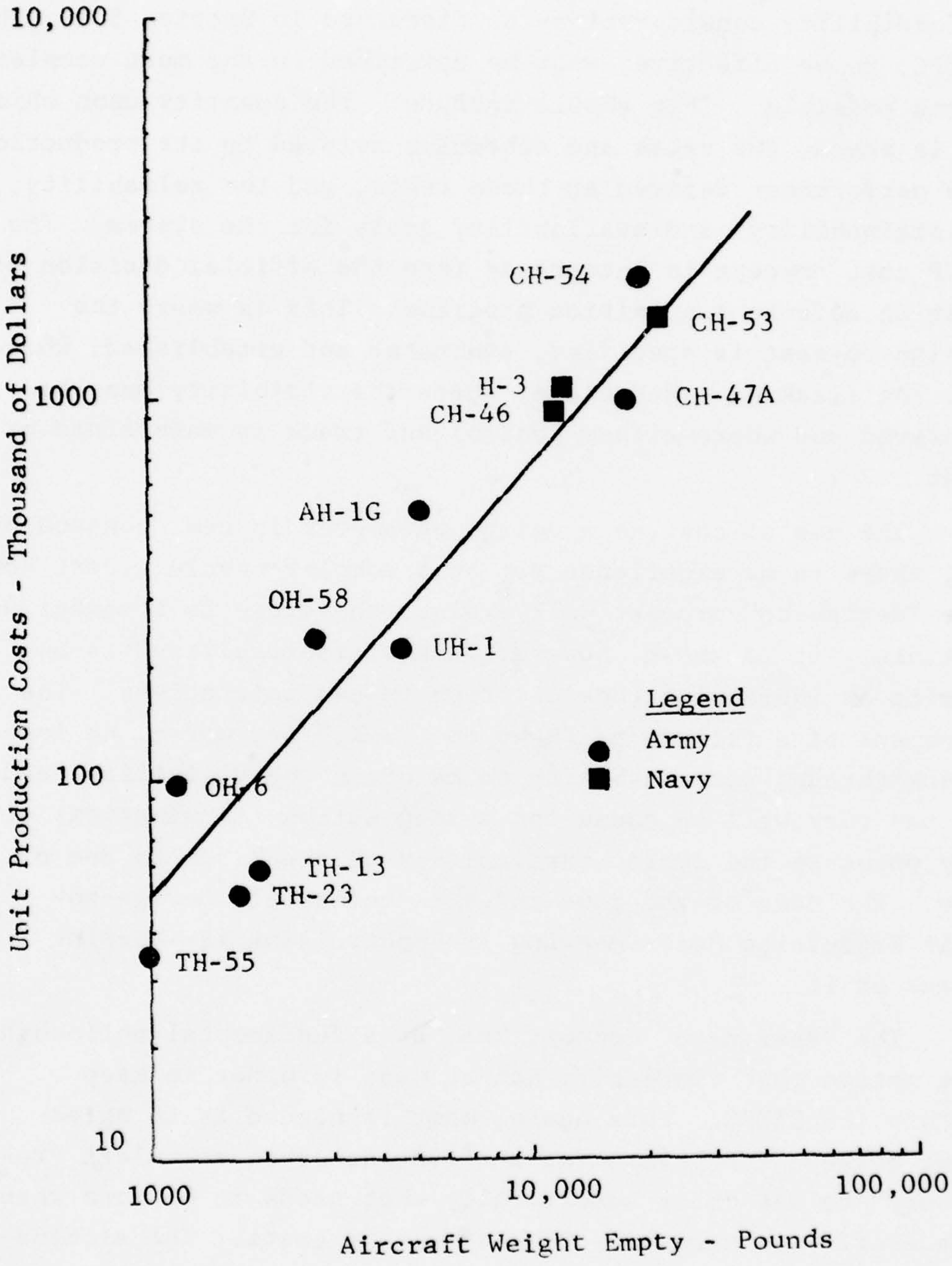

Figure 5-13

HELICOPTER ACQUISITION COSTS

affordibility considerations as discussed in Section 5.1. The DTUPC, to be effective, must be described in the most complete terms possible. This should include: the quantity upon which it is based, the rates and schedules related to its production, the performance derived at those costs, and the reliability, maintainability, and availability goals for the system. The DTUP cost concept is integrated into the official decision process on defense acquisition programs. This is where the design-to-cost is specified, evaluated and established, where all the tracking takes place, where the visibility must be achieved and where either control and track is maintained or lost.

The use of cost as a design parameter is new, consequently, there is no experience yet on a complete cycle. Just how the "design-to" process will evolve, therefore is somewhat uncertain. It is known, however, that "affordability" is becoming an increasing consideration in new initiatives. The prospect of a failure to "keep on track," or, worse, to lose track through some inability to maintain the visibility needed may very well be cause for a stop action (termination) at any point in the cycle, particularly at check points one or two. The name of the game today is definitely Design-to-Unit Production Cost--meeting it--controlling it--keeping track of it.

The "design-to" concept has, as a fundamental philosophy, the notion that trade-offs can be made in order to keep within the DTUPC. Here again, what is needed is an agreement between the government and contractor on an "Alert Procedure" to determine specifically what needs to be done when trade-offs are necessary to stay within costs. The alternatives which have been studied for accomplishing this vital design-to-cost aspect generally involve a spelled out configuration control agreement in the contract. The objective is to define those areas in which the contractor can perform

trade-offs at his option, and those which would require prior approval by the government.

Defining the limits for trade-off of reliability and maintainability parameters is of critical importance. The unit production price limits the cost of spares, the amount of built-in test equipment (BITE), and the functional reliability that can be designed into the system for meeting the operational availability requirement. The operational scenario, along with unit level reliability, defines the expected number of system faults that will have to be serviced within the defined ownership costs. Required system availability further constrains reliability and establishes the maintenance and supply considerations that will have to be designed into the system. All these factors, and more, enter into the initial design trades if affordable systems are to be acquired. By setting a unit production price and designing to it, the BITE, redundancy, and maintenance concepts that can be utilized are automatically limited. The offsetting factors have to be spares and manpower or availability.

Since the design-to concept would require unit production cost to be traded against R&M parameters, it has been proposed (Ref. 5-7) to convert R&M characteristics into operating and maintenance costs. As discussed in Section 5-3, R&M significantly impacts support costs. By designing to both a unit production and an operating and maintenance cost, the system's life cycle cost can be reduced. This requirement could be placed on the contractor as a "design to" (direct) operating and support cost. This "design-to" cost would not represent total ownership costs, but only those costs directly related to the contractors equipment development.

As part of the conceptual phase's Request for Proposal, competing contractors could receive the following requirements:

1. Mission objective,

2. Operational requirements,

3. Minimum acceptable performance requirements,

4. Minimum acceptable reliability requirements,

5. Minimum acceptable availability requirements,

6. Maximum acceptable unit production costs and associated total production quantities and rates exclusive of spares,

7. Maximum acceptable direct O&S costs and logistic restrictions, if any.

Given these requirements, contractors would synthesize a design and maintenance concept that would meet minimum acceptable performance, reliability and availability requirements.

In considering why O&M and life cycle costs (L.C.C.) have been receiving less emphasis, to date, than acquisition cost plus field reliability, there are at least four major areas which require better understanding and more precise quantification before we can talk more meaningfully about L.C.C.: 1) how do we consider the dollar impact equipment availability? 2) what "indirect" costs are included in the model? and how "fixed" are some of these? 3) what equipment life should be used? 4) what discount factors should be used? 5) what project budgeting function should be applied?

The answers to each of these questions obviously can have major impact on the estimated O&M costs, variations of over an order-of-magnitude would certainly be expected, and the answers would have major impacts on equipment requirements and selections.

Nonetheless, major strides forward are being made at formulating L.C.C. models. However, the input data used

for planning purposes probably results in errors of 3-10 times, on the low side. (Ref. 5-8)

Consider the following breakdown:

Possible L.C.C. Estimating Errors

	Est. Errors	Impact on L.C.C.
Field Reliability	2-10	1.5-5
Support Equipment	1.5-3	1-1.5
Personnel Efficiency	2-4	1.5-2

Possible Est. Error 3-10x

In spite of the difficulties noted above, it is felt that the current focus on acquisition cost must be balanced by a corresponding focus on support cost. Otherwise, L.C.C. will tend to increase as R&M suffers in the pressure to maximize performance for minimum development and acquisition dollars.

Present inability to estimate true field reliability is a major roadblock in the implementation of a design to O&M cost on L.C.C. effort. Reliability assessment and prediction techniques discussed in this planning guide offer the potential to improve reliability estimates. The assessment of the operating and maintenance environment on helicopter reliability would also increase the credibility of field reliability estimates. Successful implementation of L.C.C. techniques offers the potential of reducing the future O&M budget. As discussed in Section 5.1, tomorrow's procurement budget will be allocated from the defense budget after the O&M costs of today's development projects are budgeted. Lack of control of O&M costs in present programs will increase budgetary pressure on future new equipment procurement.

5.5 R&M and Cost Trade-Offs

R&M program provisions impact the cost of the development and production effort, while the actual reliability and maintainability experienced for a given system will significantly impact O&M costs. Throughout the helicopter life cycle, both costs and savings can be traded-off against R&M parameters. The trade-offs should have the objective of minimizing life cycle costs.

In the real world of fixed budgets, R&M must compete for funding with other important program requirements. To ensure that R&M is adequately funded, benefits resulting from R&M provisioning should be both visible and quantifiable. In addition, within the dollars allocated for R&M, various R&M provisions can be traded-off to attain the greatest R&M benefit for the expenditure. As an aid to providing visibility and quantification to R&M provisions, cost models can be very useful. Both life cycle and R&M trade-offs within program phases are discussed.

5.5.1 Life Cycle Trade-Off Concepts

Figures 5-14 and 5-15 illustrate the relationship between reliability (MTBF, θ_i), maintainability (MTTR, τ_i) and cost. Figure 5-14 shows that as a system is made more reliable, everything else being equal, the operating costs will decrease since there are fewer failures. At the same time, acquisition costs (both development and production) must be increased to attain the increased reliability. At some point, each acquisition dollar (and, in particular, development cost dollar) spent on increasing reliability will result in exactly a dollar saved in operating costs. This point represents the reliability for which total costs are minimum. Note that there are steps in attaining reliability which are of varying difficulty and cost. The cheapest increase in reliability would be taken first and the most expensive last. Therefore, the cost of reliability must have an increasing upward slope, whereas the total field support cost has a decreasing slope.

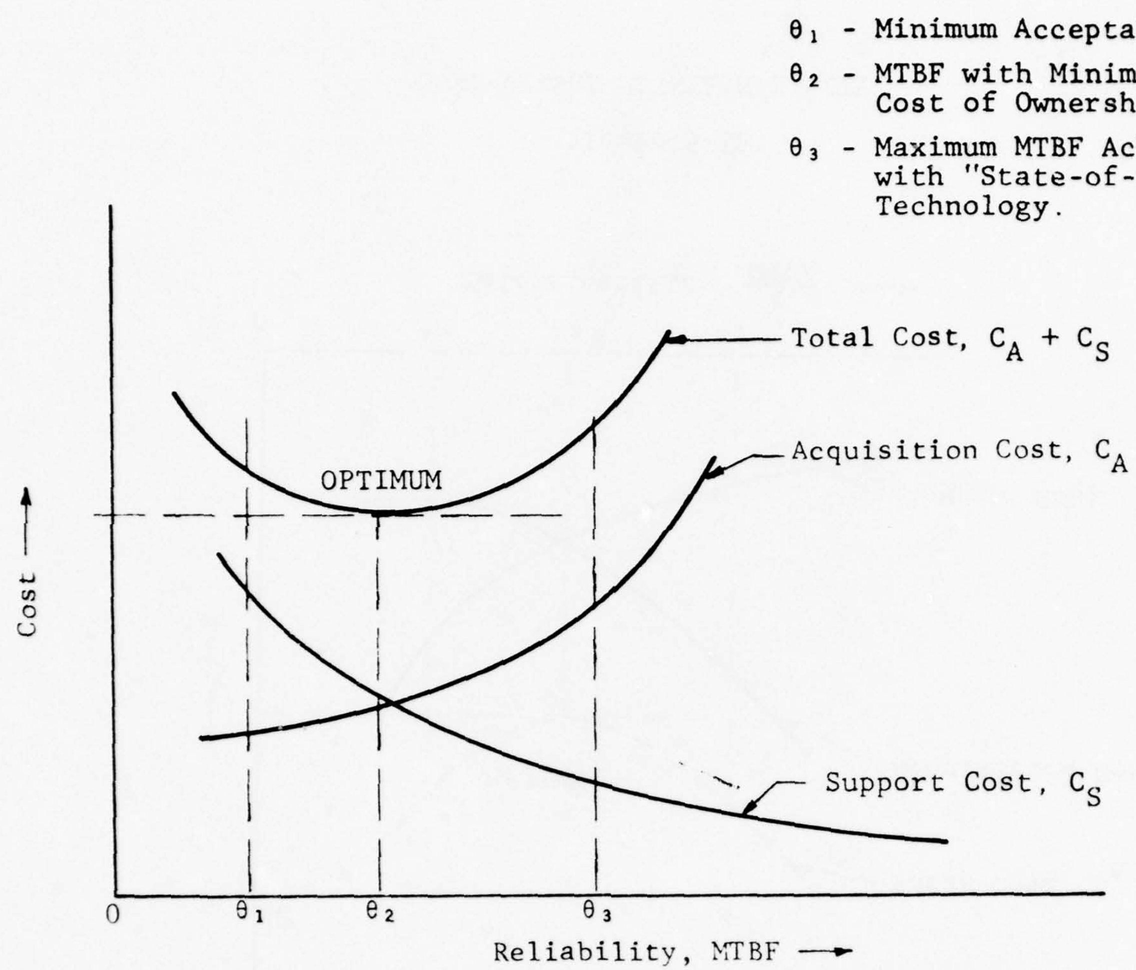

Figure 5-14

COST VERSUS RELIABILITY

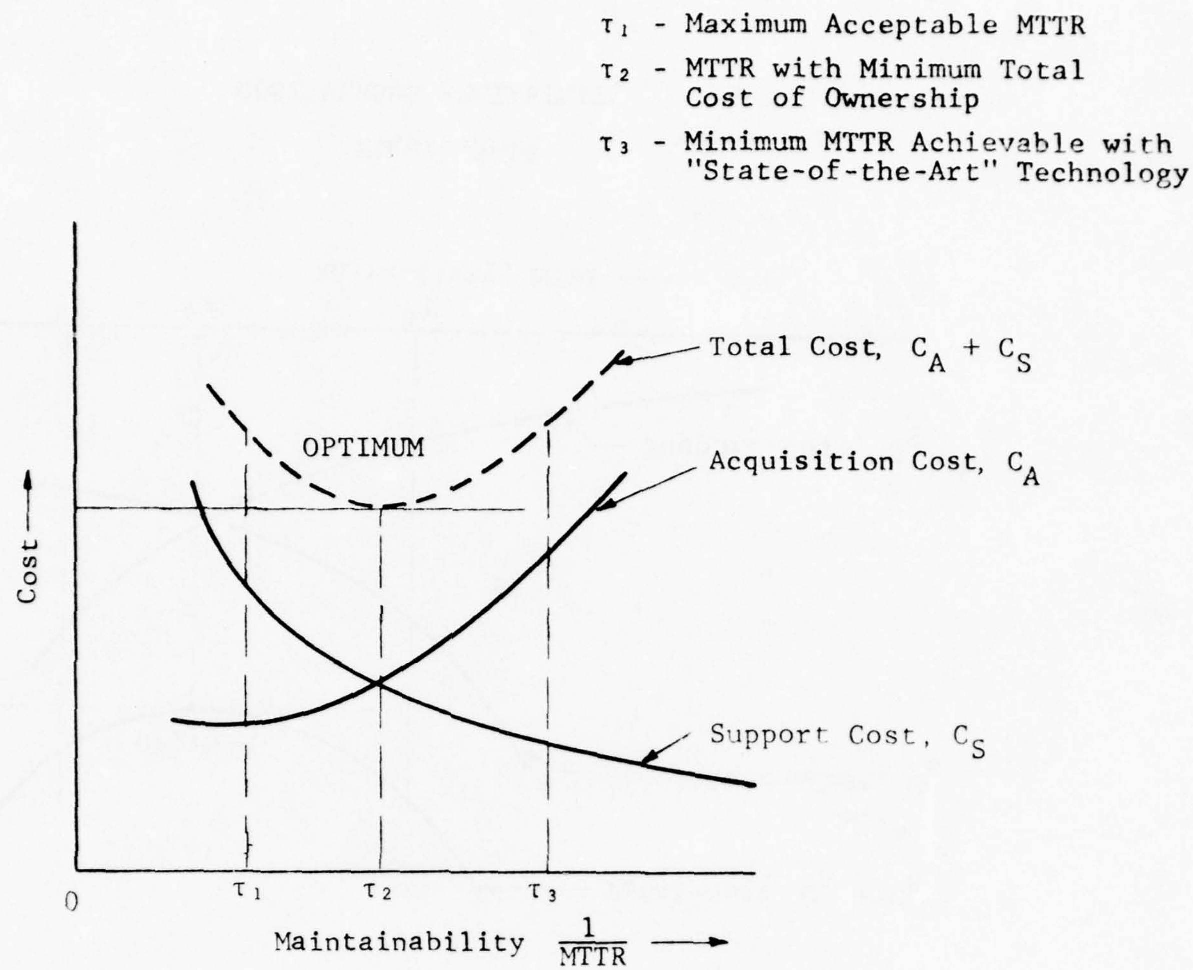

Figure 5-15

COST VERSUS MAINTAINABILITY

Essential to effective trade-off studies is the definition of each step and the development of accurate and detailed reliability/cost curves for systems that show the sensitivity and breakpoints of critical reliability and maintainability factors, such as those shown conceptually in Figures 5-14 and 5-15. Simplified expressions based on life cycle cost modeling previously discussed, have been derived for acquisition costs versus MTBF in recent studies. These expressions are depicted in Figure 5-16. Also shown is the equation derived for the cost of field support.

Optimum MTBF expressions for θ_2 based on the linear and nonlinear cost equation have been derived by combining the acquisition and support expressions to define total cost and determining the minimum point by the use of the calculus.

In recent studies the expressions for θ_2 are:

$$\theta_2 = \sqrt{\delta} \quad \sqrt{\frac{K_2 N \theta_1 T Z}{D_1 + UN}} \qquad \text{Linear}$$

$$\theta_2 = (\delta)^{\frac{1}{m+1}} \left[\frac{K_2 N T Z (\theta_1)^m}{m(D_1 + U_1 N[\theta])} \right]^{\frac{1}{m+1}} \qquad \text{Nonlinear}$$

Similar expressions are being derived for optimum values of MTTR (τ_2). See Figures 5-14 and 5-15.

Generation of sensitivity curves involves the use of R&M models detailed enough to allow the quantitative assessment and graphical presentation of such factors as:

- Design factors of safety
- Factory tests
- Reliability growth tests
- Equipment break-in

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$$C_A = \left[D_1 + U_1 N\right]\left[\frac{\theta}{\theta_1}\right]$$

linear

$$C_A = \left[D_1 + U_1 N(\rho)\right]\left[\frac{\theta}{\theta_1}\right]^m + \beta$$

non-linear

D_1 is the cost of development of an existing equipment with MTBF of θ_1

U_1 is the unit production cost of an existing equipment with MTBF of θ_1.

N is the number of units to be produced.

ρ is an adjustment factor which takes into account the volume effect due to N of procurement under consideration being different from N of existing equipment procurement ($\rho \geq 0$).

m accounts for the non-linearity of the acquisition cost curve ($m \geq 0$)

θ is the MTBF of the equipment under consideration.

θ_1 is the minimum acceptable MTBF (i.e., that of the existing equipment), $\theta_1 < \theta$

β is the initial cost of setting up the project (i.e., feasibility studies, cost studies, etc.).

NOTE: *D_1, U_1, and β are to be given in present day dollars to account for inflationary (or deflationary) changes in cost*

$$C_S = k_1 + k_2\left[\frac{NTZ}{\theta}\right]\delta$$

$k_1 = C_1 + C_2 N$ cost of initial spares and support equipment

$k_2 = f(C_3 + C_4 + \ldots + C_8)$ average field support cost per failure

$\frac{NTZ}{\theta}$ average number of equipment failures

T equipment service life in hours

Z utilization factor (duty cycle)

δ discount/escalation factor

Figure 5-16

ACQUISITION COST VS MTBF EXPRESSIONS

Because of the impact the processes, controls and tests have on reliability and cost, it is especially important to quantize these factors and perform trade-off studies. For example, factors which relate system reliability to the three levels of reliability defined in Section 3.3 can be analyzed. Figure 5-17 gives an example of reliability versus cost curves where reliability (MTBF) and cost as a function of R&M program levels are shown for several system design configurations. Note that the figure presents general concepts, prepared to illustrate the trade-off process; it is not intended to present actual helicopter systems. This figure indicates that a level 2 (see Section 3.3.1) program represents the most cost effective approach. Actual trade-off curves can be developed through a review of helicopter design characteristics in conjunction with R&M program provision data presented in this guidebook.

Like reliability, increasing maintainability causes increased acquisition costs and reduced operating costs. Maintainability is generally measured in Mean-Time-To-Repair (MTTR); the less time required to repair an item (the smaller MTTR), the more maintainable the item. If one takes the reciprocal of MTTR to obtain a variable which increases with maintainability and with cost of attainment in acquisition, exactly the same type of curves are obtained as for reliability (Figure 5-14).

As with reliability, generation of maintainability/cost sensitivity curves for actual equipment will involve using models detailed enough to allow the quantitative assessment of such factors as:

- Built-In Test Equipment (BITE)
- Modularization
- Level and Type of Replacement Element
- Accessibility
- Alignment Procedures
- Maintenance Skill Levels and Instructions
- Automatic Ground Equipment (AGE)

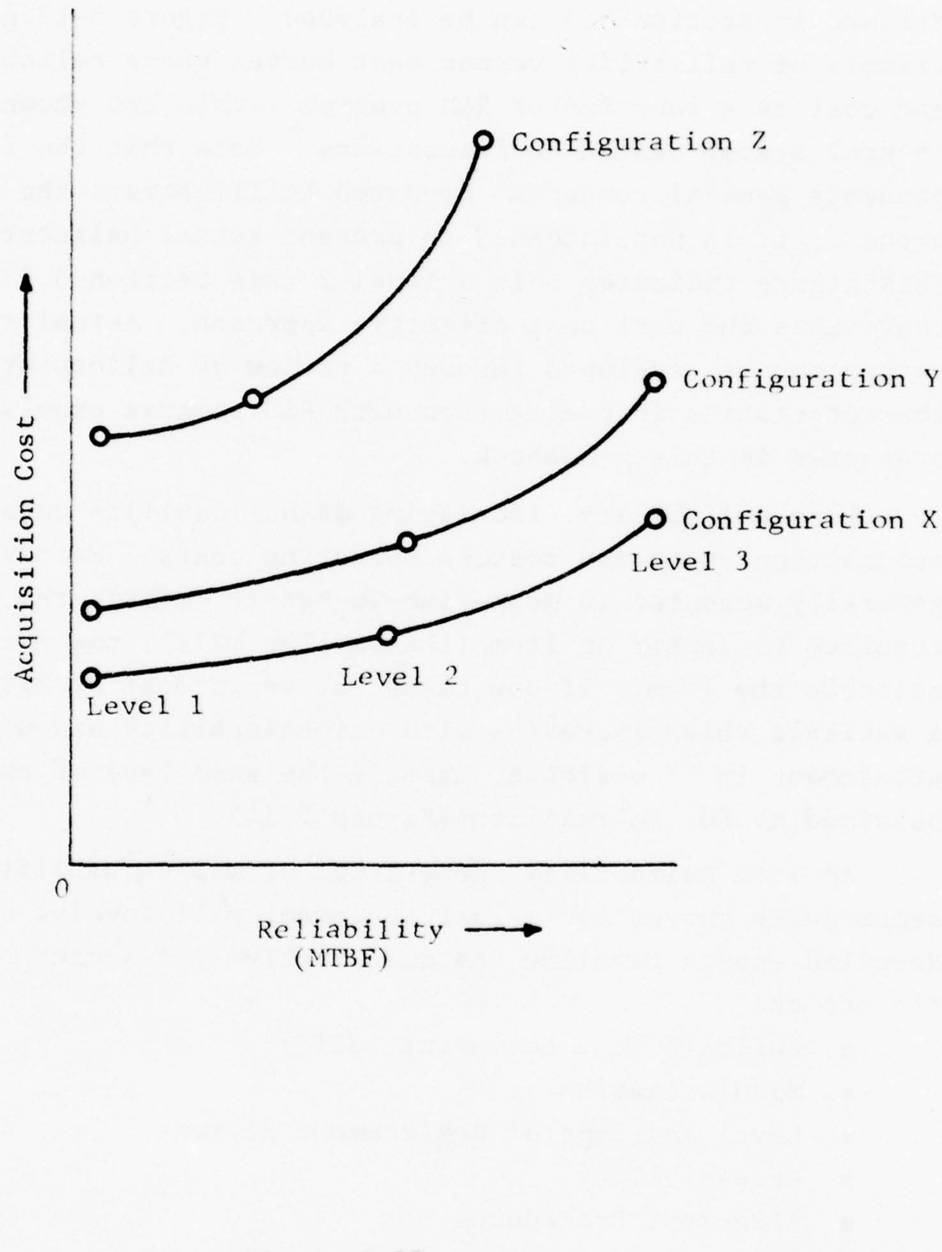


Figure 5-17

RELIABILITY VERSUS COST AS A FUNCTION OF RELIABILITY PROGRAM LEVELS

Relationships can be derived for determining cost variations with equipment performance assuming various technologies and reliability and maintainability approaches. Relationships can also be derived defining how reliability and maintainability vary with performance (or with complexity, which is in turn dependent on performance) with cost held constant. The resultant reliability and maintainability for any given performance can be referred to as the baseline reliability and baseline maintainability.

The trade-offs between reliability and maintainability must also be considered. For this purpose, additional relationships are derived which state how relative cost changes as reliability or maintainability is varied from the baseline. Figure 5-18 provides an example of the reliability/maintainability trade-off process. Figure 5-18 can be interpreted as as resultant cost allocation approach for optimizing MTBF and MTTR. The isocost and isoavailability curves shown in Figure 5-18 define the appropriate mix of MTBF and MTTR to optimize costs. Note that availability as used here involves both MTBF and MTTR and is expressed mathematically as:

$$\boxed{A = \frac{MTBF}{MTBF + MTTR}}$$

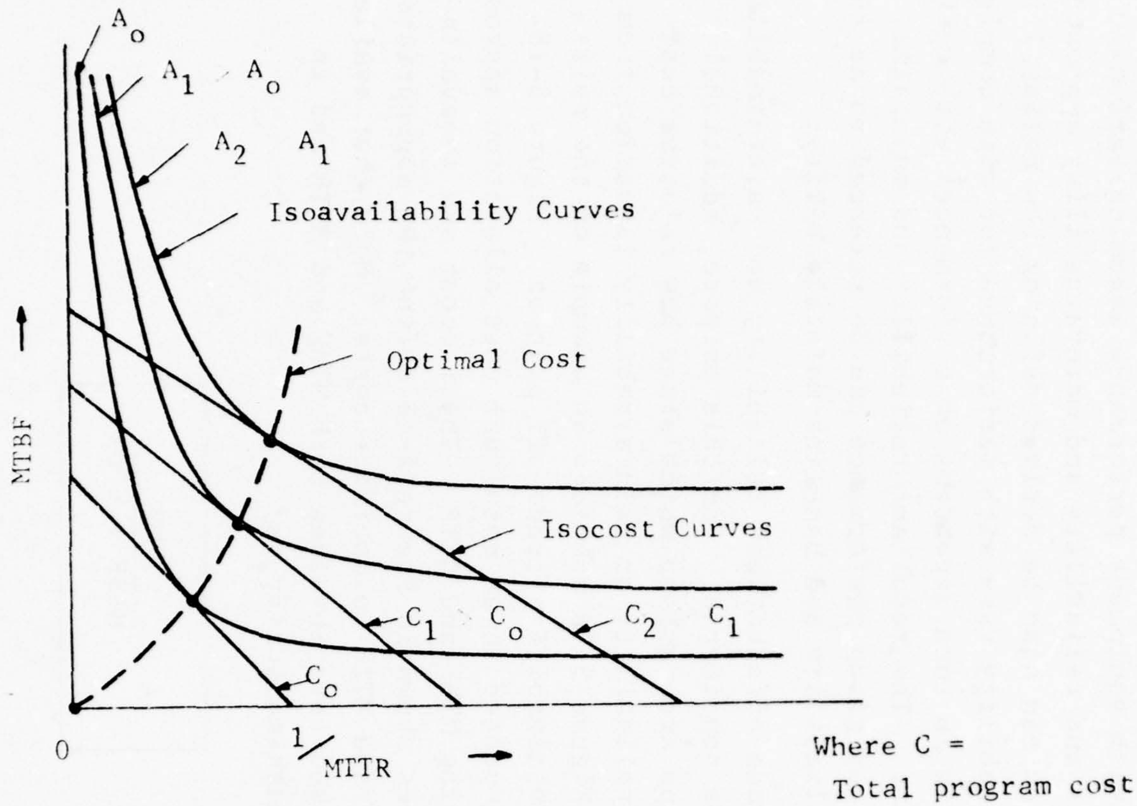


Figure 5-18

OPTIMUM COST ALLOCATION APPROACH

Figure 5-18 indicates that the optimum R/M approach occurs at the point of contact between the isoavailability and iso-cost curves. The actual isocurves for specific equipment can be generated using computerized calculation procedures in conjunction with the reliability, maintainability and cost models previously described.

5.5.2 Optimum Allocation of R&M Provisions within Budgetary Constraints

A fundamental premise of this section is the assumption that all hardware conceived and designed by man has inherent flaws that can lead to failures later. Finding these flaws and correcting them requires effort either in manpower or equipment.

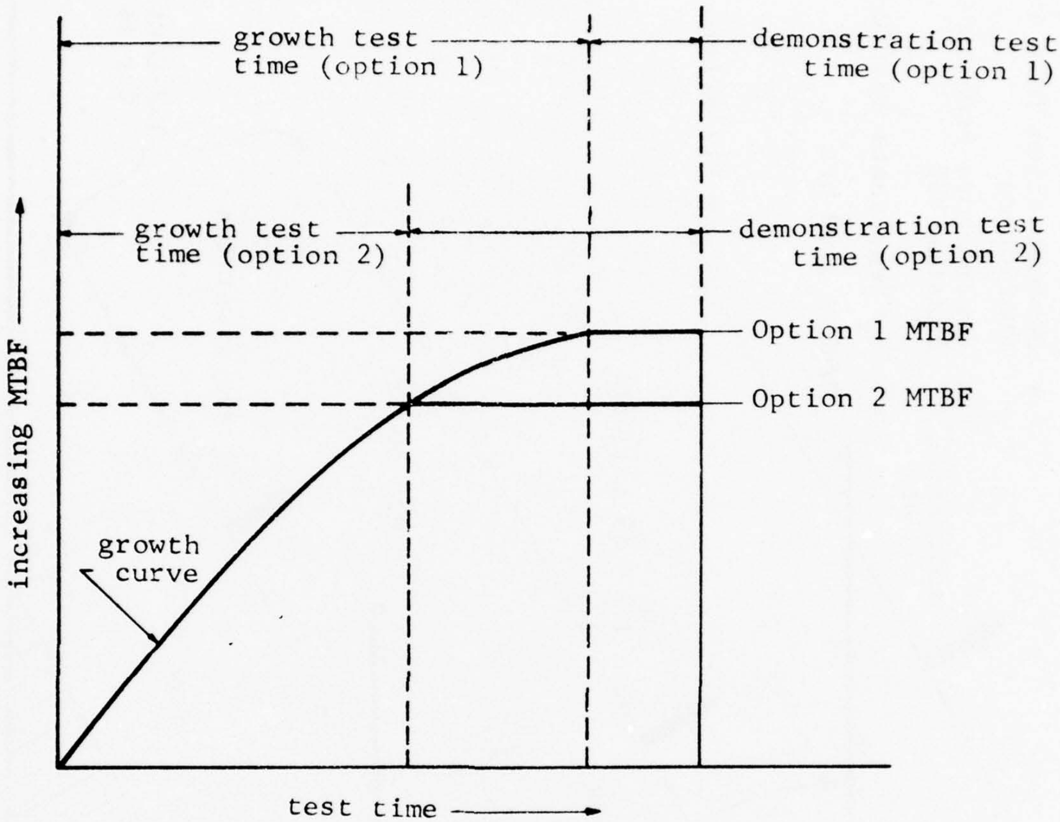
When resources are not allocated for reliability effort, all the inherent flaws in the design or those introduced during production will literally go out the door--eventually to be uncovered in the field.

This planning guide has discussed R&M provisions for all phases of the helicopter's life cycle. Not only is reliability testing discussed, but prediciton, assessment, component control and assurance procedures are described. The provisions are designed to uncover reliability defects or to control the development or production process to assure that reliability is not degraded. The R&M planner knows the total resources available for the development effort and the budget allocation for R&M activities. Within the budget allocation, alternate R&M provisions are available to the planner, the objective being to optimize helicopter R&M characteristics.

To optimize helicopter R&M characteristics, specific and detailed allocation and trade-off analyses must be made within fixed budgeting constraints. To illustrate the allocation

and trade-off process, consider the problem of optimizing growth test time and demonstration test time with respect to a total fixed test time. For purposes of this example it is assumed that both growth test costs and demonstration test costs are proportional to test time. Figure 5-19 illustrates two options available to the R&M planner.

If the original plan specifies that reliability should be demonstrated at a low confidence level (e.g., 60%), reliability growth testing could be emphasized. Plotted in Figure 5-20 is the amount of test time (growth and demonstration) that is necessary to achieve the required MTBR. The estimates were based on a 3 year program with several types of growth tests used to establish the test time requirements. (Ref. 5-5) The concavity of the iso-MTBR curves indicates diminishing test effectiveness for extreme test durations. Superimposed on Figure 5-20 are iso-cost curves. The constant costs are based on 3800 \$/hr rate for growth testing and a 200 \$/hr rate for demonstration testing. The The iso-cost curves are represented by a series of parallel lines of increasing cost away from the origin (0) while the iso-MTBR curves are decreasing as they approach the origin. The minimum cost required to achieve a specified MTBR is the point of tangency between the iso-cost and iso-MTBR curves. For example, point C in the figure represents the minimum cost (9 million dollars) required to achieve a required MTBR of 1000 hours. It is achieved if 6500 hours of demonstration tests are specified and approximately 2000 hrs of growth testing is planned. If a lesser number of demonstration test hours are planned, the contractor must plan additional testing to achieve a higher actual level of reliability to be assured of passing the test with 80% confidence. For example, the total expenditure required to achieve an MTBR* of 1000 hrs, with only 4000 hrs of demonstration testing planned, is 10.1 million dollars.



option 1	maximizes reliability growth testing and minimizes demonstration testing - results in relatively high MTBF at low confidence
option 2	minimizes reliability growth testing and maximizes demonstration testing - results in a lower MTBF at higher confidence

Figure 5-19

R & M PROGRAM TRADE-OFFS

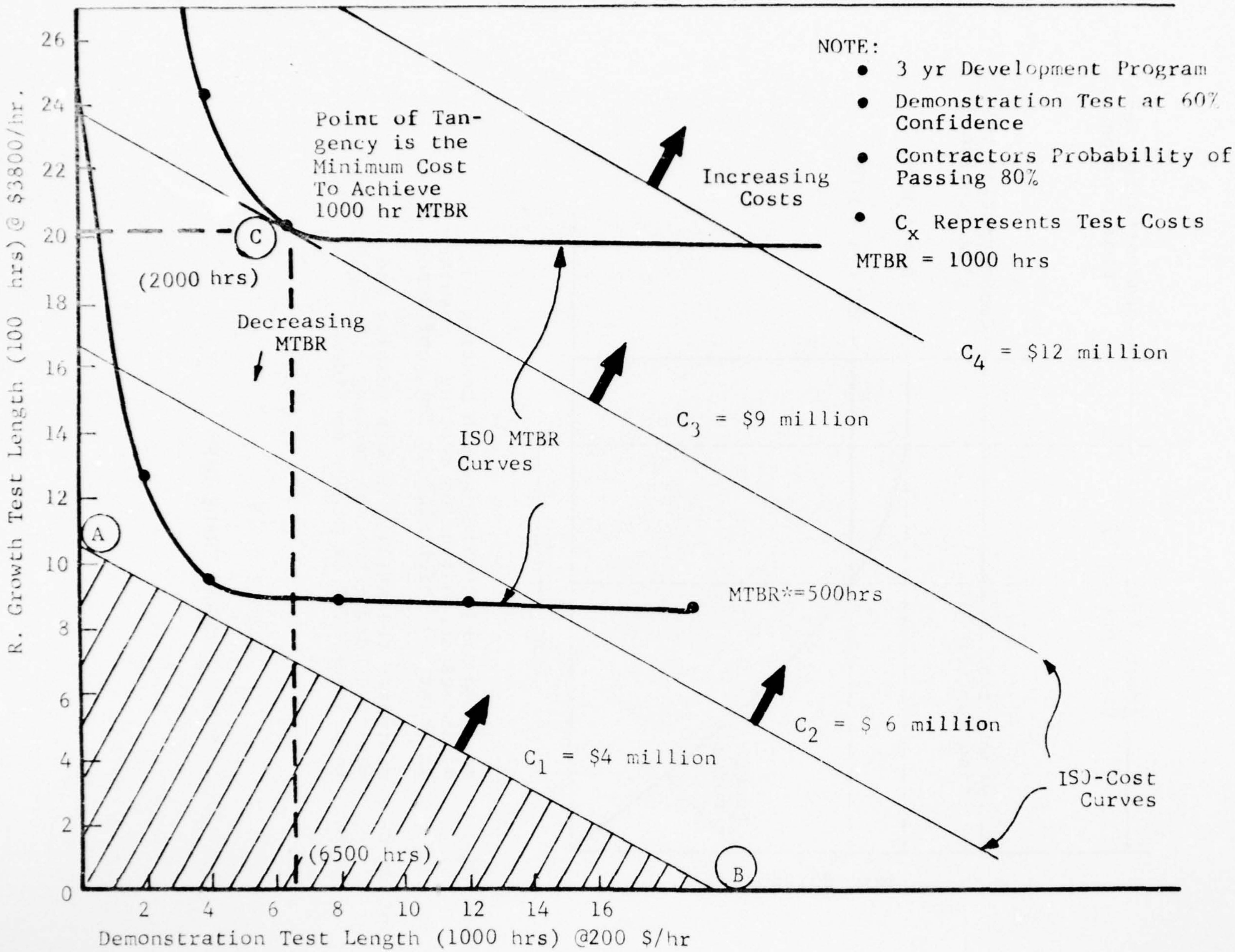


Figure 5-20
ISO-MTBR AND IS)-COST CURVES FOR RELIABILITY TESTING PROGRAM

The iso-cost curves in Figure 5-20 illustrate another characteristic of R&M program planning, i.e., if the R&M funding is inadequate, it may be impossible to achieve and demonstrate the required MTBR. The shaded area A-O-B in Figure 5-20 represents feasible combinations of growth and demonstration test hours possible with a 4 million dollar R&M budget. It is not possible to demonstrate an MTBR of 500 hours with the R&M allocation. Figure 5-21 indicates it would be possible to demonstrate a MTBR of 500 hrs at a confidence of 30%. The requirement could be met with a 2.9 million dollar expenditure and a 1500 hr demonstration program with 650 hours of growth testing scheduled for the development effort.

The example presented illustrates the high cost of R&M testing for helicopters. The only method considered to improve reliability in the previous example is reliability growth testing. Section 3.3 lists 18 R&M provisions applicable to helicopter development programs. Many of these provisions involve analytical determination of failure modes or the use of design check-lists and reviews that will lead to improved reliability. The R&M planner must determine the proper mix of analytical and test effort to optimize helicopter reliability. Iso-cost and iso-MTBR curves could be constructed for the alternate reliability effort (analysis and test) in the same manner as the curves in Figure 5-20 were constructed. These curves are shown in Figure 5-22 Note the lines of constant MTBF are again concave due to the diminishing returns from an R&M program that emphasizes only analysis or only test. The point of tangency (C) between the iso-cost and iso-MTBF curves represents the minimum cost to achieve a 500 hr MTBF. The example indicates T_1 growth test hours and A_1 analytical effort should be scheduled.

The same type of iso-curves can be constructed for the production phase of the helicopter life cycle. Let us assume 200 transmissions are required to be produced in a

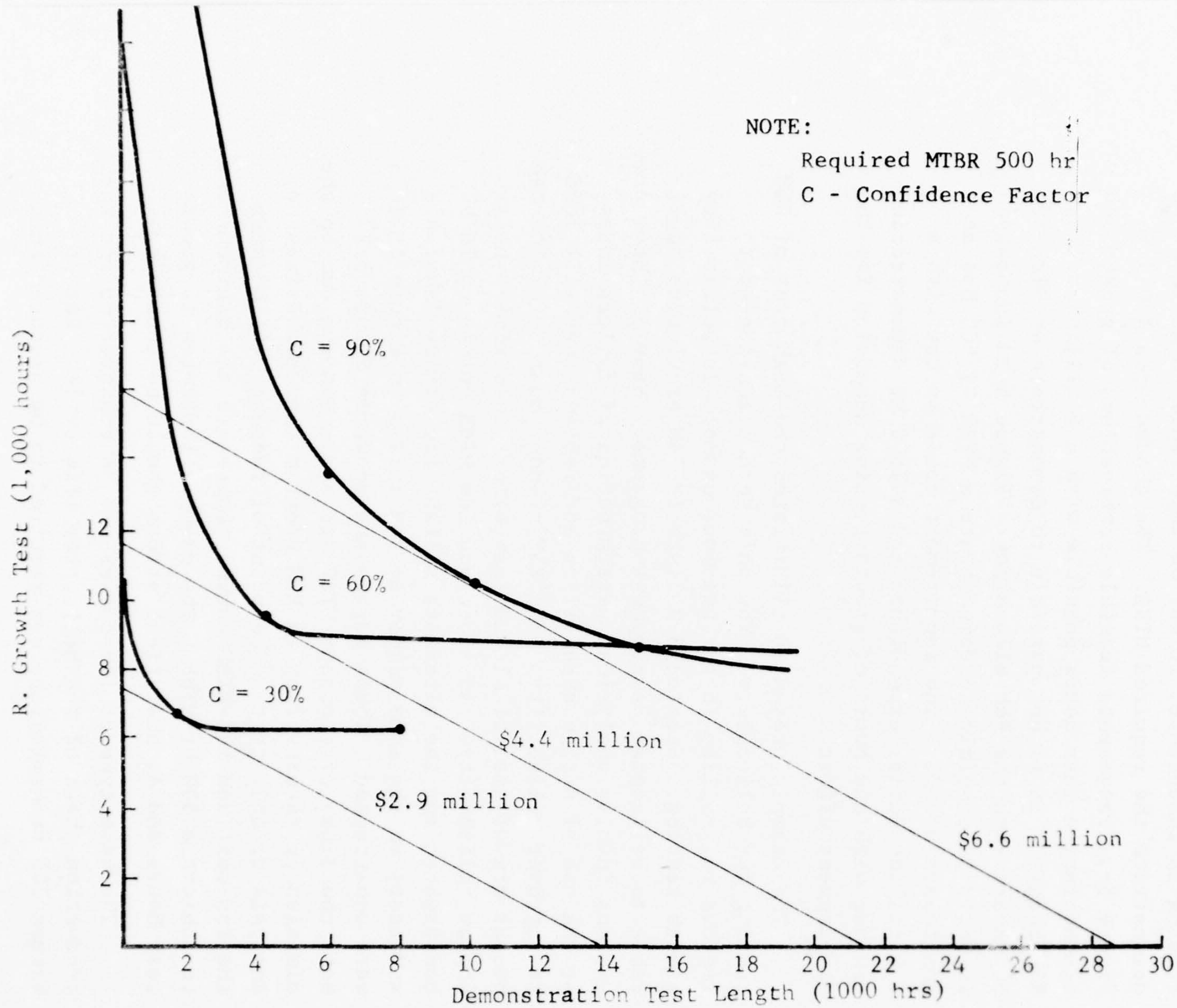
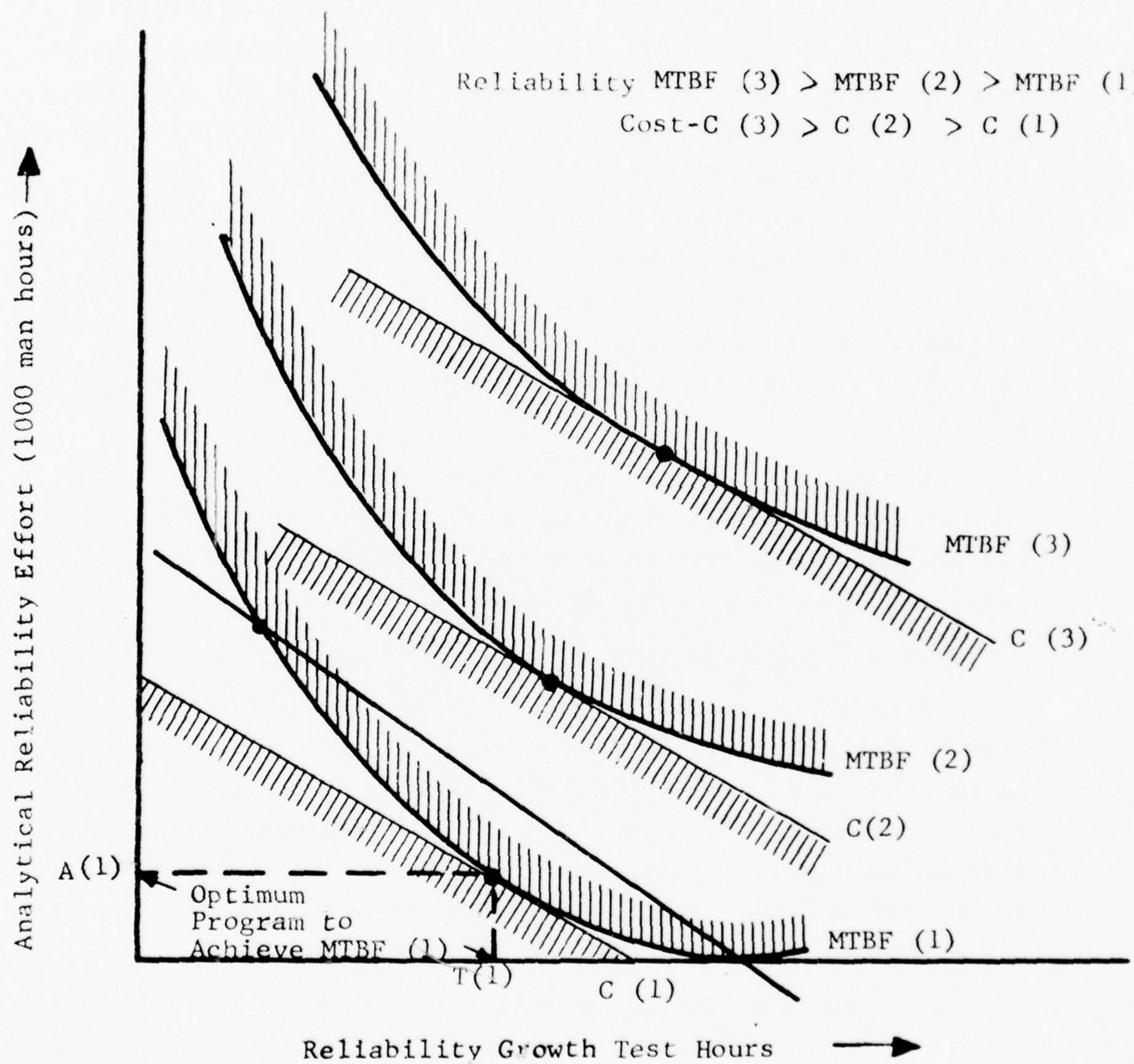


Figure 5-21

THE EFFECT OF CONFIDENCE FACTORS ON PROGRAM COST



Note: Analytical Effort includes FMEA, Prediction, Allocation, Etc.

Figure 5-22

ISO-COST AND MTBF CURVES FOR A RELIABILITY DEVEOPMENT PROGRAM

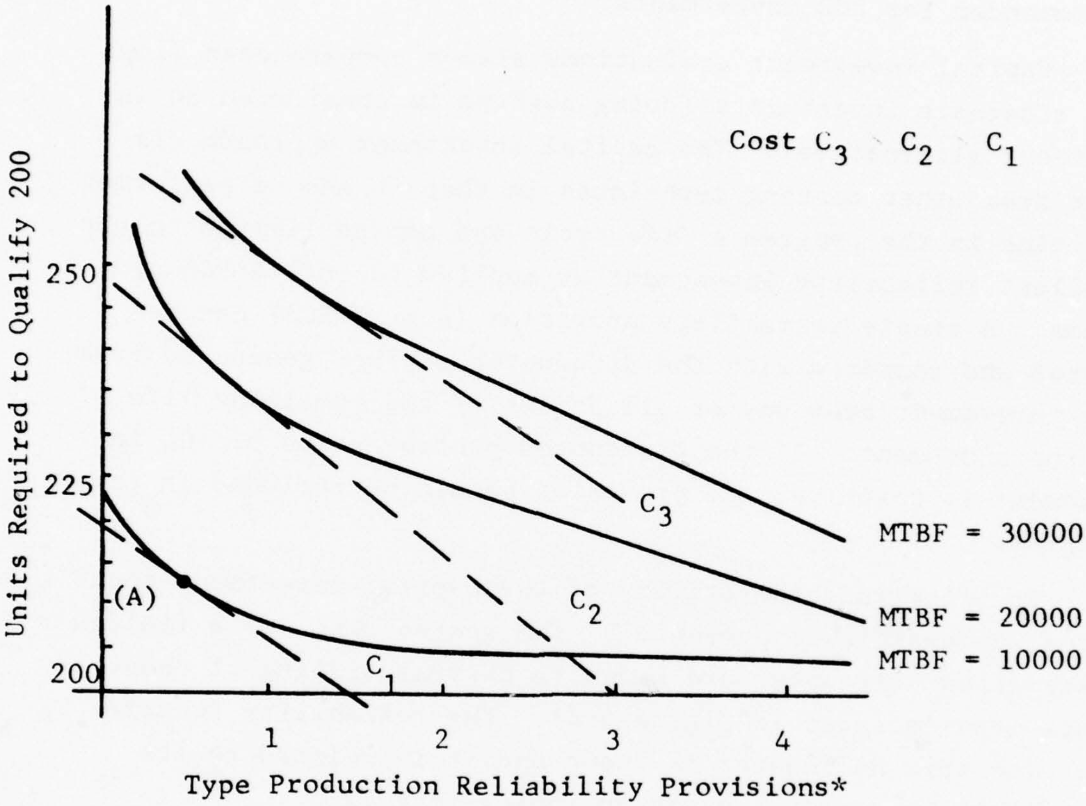
year. Prior to final assembly, extensive "break-in" testing is scheduled. If no special pre-test sub-assembly screening test or special inspection procedures are scheduled, it is known that 225 units must be produced to qualify 200 units at a specified reliability. Special production reliability provisions can reduce the number of "extra" units required to be produced, but it is also known the screening provisions can be costly and no level of screening would be 100% effective. In other words, concave iso-MTBF curves can be expected. The iso-curves are plotted in Figure 5-23. Again the point of tangency between the iso-cost and iso-MTBF is the least costly method of achieving the required MTBR. For instance, 213 units will be produced while the production reliability effort required is somewhat less than a type 1 effort.

It should be pointed out that production costs have been reduced although reliability provisions were added to the program. The savings resulted from less scraped units being required to achieve the production goal.

5.5.3 An Engineering Economics Approach

Reliability and maintainability program provisions can also be treated as a capital investment, Ref. 5-9, (i.e., an investment of funds with the intention of incurring a greater return). The benefits of the investment can be reduced maintenance cost reduction in required force size or improve safety. There are several ways of evaluating a potential capital investment. They include:

- The computation of return on investment. This is the percent of the investment which is returned each year the investment is in force.
- The payback period. This is the time required to recoup the investment at zero discounting.
- Present value method. This is the discounted return, less the discounted cost of the investment.



*Note 1. (Engines)
2. (A) is Point of Tangency Between C_1 and MTBF = 10000

Figure 5-23
PRODUCTION RELIABILITY COST TRADE-OFFS

Discounting factors are usually applied to cash flow to account for the time values of money. Discount factors between 8 and 10 percent are used, and the latter figure is recommended for DOD investments.

Capital investment evaluations always compare cash flows for alternate investments (doing nothing is considered an investment alternative). The capital investment approach differs from other costing techniques in that it can be performed any time in the program's life cycle and can be limited to the smallest reliability investment or applied to entire R&M programs. A single reliability provision (e.g. FMECA) can be costed and compared with the discounted savings generated from the investment over any or all phases of the remaining life of the equipment. If the discounted present value of the investment is positive, the provision should be included in the program.

To illustrate the utility of the capital investment technique, an example is presented. The spares cost of a fielded observation helicopter are known (a partial listing of these costs were included in Figure 5-8). The reliability requirement for this helicopter is known and it is related to its field failure rate using the following formula

$$\lambda_f = K/MTBF + \lambda_{om}$$

where

MTBF	=	is the required reliability
λ_f	=	field failure rate
λ_{om}	=	failure rate due to operating and maintenance errors
K	=	field failure adjustment factor

The cost of a reliability growth test program has been estimated in Reference 5-10 as a function of the required

MTBF. These costs were allocated over a three year development program and compared with the savings generated from a reduction of required spares as predicted using the above failure rate formula, an average cost for the spares, a fleet flying schedule, a production schedule and an estimate of fleet life. Results of the analysis are shown in Figure 5-24. A range of possible savings results because minimum, maximum and expected costs and savings were estimated for the investments. The range can be considered the risk of the investment due to uncertainties in fleet life, development cost and time overruns, and the range of actual MTBF possible, since reliability was demonstrated at a low confidence level. The optimum savings resulted in an MTBF of 500 hours where the expected savings, after 4.4 million dollar expense, is approximately 8 million dollars. For extreme reliability requirements (1500 hours MTBF), Figure 5-24 indicates there is a possible risk that the investment will not pay off.

5.6 Life Cycle Cost Programs

In the procurement of new system and/or improve fielded systems, three basic life cycle cost program approaches should be considered.

(1) Establish requirements to minimize acquisition cost

(2) Establish requirements to minimize total life cycle cost

(3) Establish requirements to minimize maintenance support

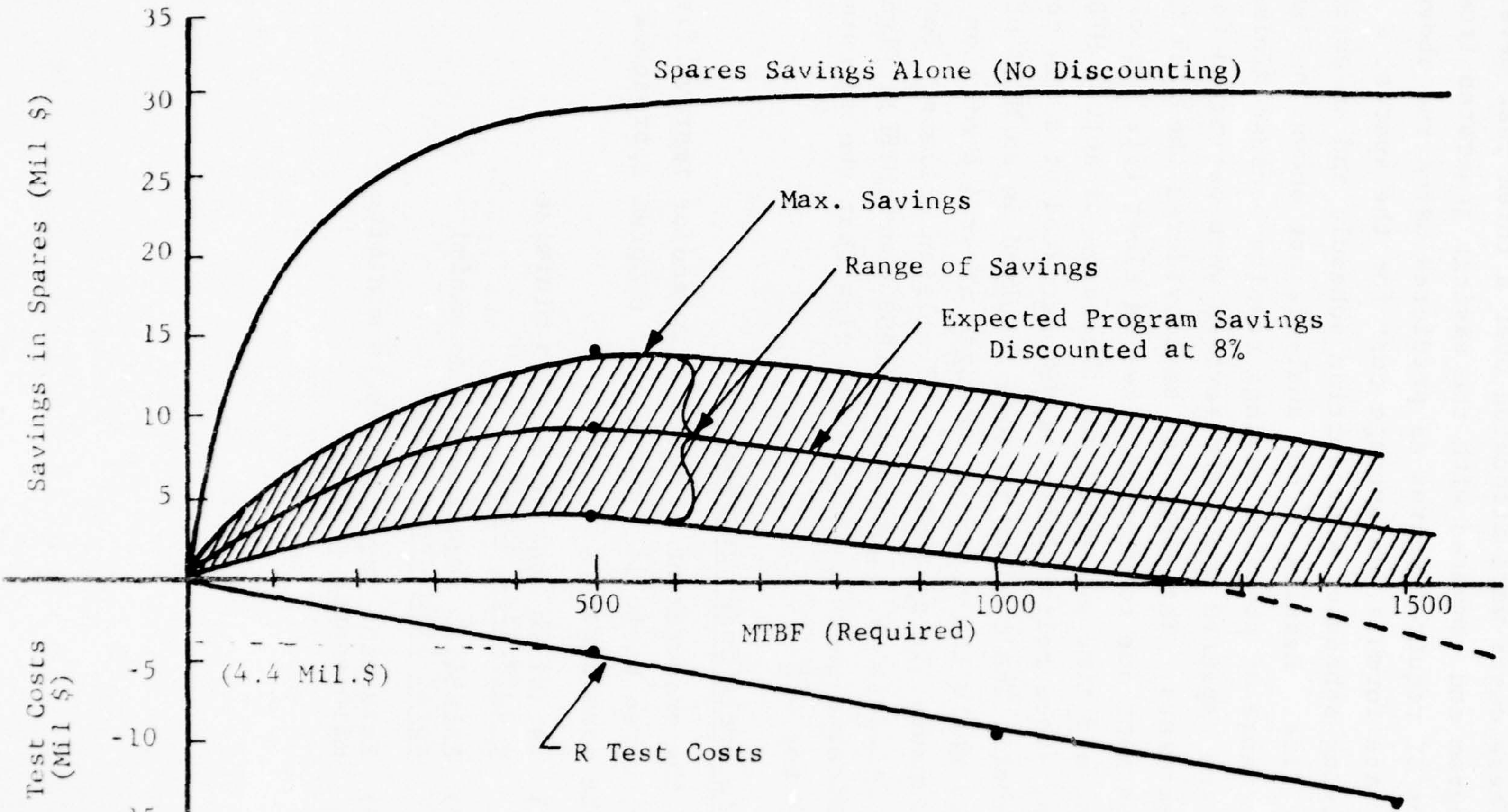


Figure 5-24

RELIABILITY INVESTMENT EVALUATION

These approaches are illustrated in Figure 5-25.

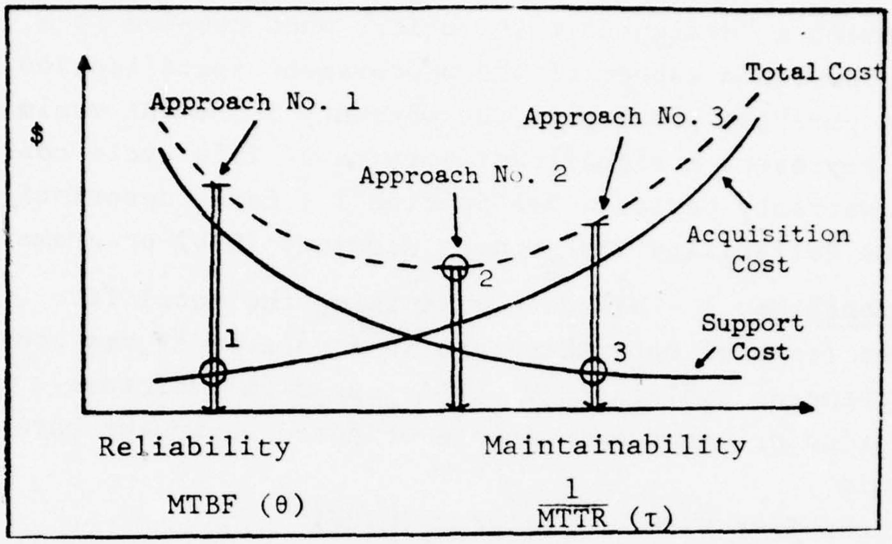


Figure 5-25 THREE BASIC APPROACHES OF AN LCC PROGRAM

Synoptic characterizations of the three approaches are as follows:

Approach No. 1 - based on minimizing the acquisition cost, can be characterized as the old military style "low bidder" approach -- which has the effect of producing the lowest possible acquisition cost (development and production) consistent with achievement of a specified functional performance. Salient features of this approach are a low development-cost and low unit-production cost typically coupled with a requirement (standard procedure in later years) for special external test equipment in order to perform fast, efficient, on-line servicing. This approach results in a relatively high cost of inventory and replacement spares (especially as older component devices are no longer produced); a relatively high cost for maintenance (much of which is performed on-line), a high cost in personnel (numbers and also in terms of skill level because these people become effective only when they become "component specialists"), and a high cost of repair management (which includes training, scheduled maintenance, documentation, and logistics).

The low bidder approach to source selection can be made to complement a "design to cost" effort when coupled to a warranty provision aspect of the procurement specification, since the purchase price plus the warranty increment would actually represent a significant portion of life cycle costs over the warranty period. See Section 5.7 for a description of various Reliability Improvement Warranty (RIW) programs.

Approach No. 2 - based on minimizing the total life cycle cost (cost of ownership) and is a relatively new concept in terms of application. It is based on judicious specification of those maintenance-oriented equipment parameters, viz,

- Mean Time Between Failures (MTBF)
- Mean Time To Restore
- Mean Time To Repair (MTTR)

along with provisions for an effective R&M development program, which typically starts during concept formulation, continues during the design and development stage, and is also carried on during the production phase. Approach No. 2 typically results in a cost-effective choice of an MTBF parameter which is somewhere between $\theta_1 < \theta < \theta_3$ and in a likewise cost-effective choice of an MTTR parameter which is somewhere between $\tau_1 < \tau < \tau_3$. Subscript 1 indicates a baseline system in which reliability and maintainability improvement techniques have been minimally incorporated, in contrast to subscript 3 which implies a system in which R&M improvement techniques have been applied to the maximum extent possible, thus resulting in a system whose R&M characteristics are very close to the maximum allowed by the R&M state of the art. The characteristics of the associated equipment design lie somewhere between Approach No. 1 and Approach No. 3.

Approach No. 3 - based on minimizing the total support cost. This is a new approach, and it is this approach which is most compatible with a "minimally attended" maintenance concept. Under this approach, equipment is designed with maximum maintenance-automation characteristics, including the following features: high reliability (high MTBF), high maintainability (low mean time to replace and low MTTR), a high degree of equipment modularity, automatic BIT/FIT (Built In Test and Fault Isolation Test), CM (Condition Monitoring), and automatic Remote Monitoring, with the result that equipment acquisition cost (design, development, and production) tends to be quite high. The benefit gained is a minimization in overall maintenance and logistic support cost during the life of the equipment. Salient maintenance and logistic characteristics due to the automated built-in and remotely monitored test/CM and fault isolation are: fast on-line restoration capability by means of plug-in modular assemblies, repair activities performed at relatively remote (shop or depot) facilities, a minimization in on-site maintenance manpower, probably a reduction in total scheduled (preventive) maintenance, and in maintenance personnel who tend to be more and more "systems experts" rather than "black box specialists."

5.7 Warranty Concepts and Considerations

One of the present problems with current equipment systems is the relatively low level of reliability and high level of required field maintenance. These conditions are a general outgrowth of the present low bidder approach to system procurement characterized by a low acquisition cost followed with a high field support cost.

Warranty techniques have recently been gaining acceptance in the industrial and military community and can be helpful to alleviate this situation.

Commercial consumers have used warranty preview techniques for several years, and proof of their effectiveness in improving reliability can be seen readily. This section presents a summary of some of the warranty programs, their achievements and possible pitfalls, and their relationship to a reliability improvement program.

The type of programs discussed are those involving long-term contractor commitment and incentives. Included among these are the RIW, in which the contractor is committed to performing depot type repair services for a fixed time period and a fixed price; MTBF guarantee, in which the contractor is committed to producing equipment which meets a stated MTBF or providing consignment spares until the failure rate is improved; and the Logistic Support Cost (LSC) commitment, in which the contractor makes a commitment for a specified LSC parameter (established through an LSC model) and if not met, becomes penalized either monetarily or through corrective actions, or, if exceeded receives an award fee. Some of the features of each of these programs are given in Reference 5-11 and reproduced in Figure 5-26.

5.7.1 Comparison of Procurement Methods

The major goal of all warranty programs has been to increase the reliability/maintainability of fielded equipment by providing contractor incentives, thus allowing for a more confident control of LCC and personnel needs. These incentives vary according to the warranty, but most usually consist of increased contractor profits and/or penalties for poor performance. However, these increased profits no longer are a cause of contractor-buyer conflict since the profits must now reflect reduced support costs for the contractor during the warranty period and thus increased product reliability for the buyer.

FEATURES	RIW	RIW/MTBF	LSC
Objectives	Secure reliability improvement/reduce support costs	Achieve stated reliability requirements/reduce support costs	Achieve stated logistic-cost goal
Method	Contractor repairs or replaces all applicable items that fail during coverage period; implements no-cost ECPs to improve reliability	Same as RIW, plus contractor provides additional spare units to maintain logistic pipeline	Normal Air Force maintenance; operational test performed to assess LSC; penalty or corrective action required if goals are not achieved
Pricing	Fixed price	Fixed price	Fixed price or limited cost sharing for correction of deficiencies
Incentive	Contractor profits if costs are lower than expected because of improved R&M	Similar to RIW, plus possible severe penalty for low MTBF	Award fee if goal is bettered; penalties for poor cost performance

Figure 5-26

FEATURES OF ALTERNATE WARRANTY PLANS

(Ref. 5-11)

Procurement of warranties also presents certain risks for both buyer and contractor. The risk that is assumed by the buyer is merely having paid too much for equipment which would have performed better than expected. In any case, the buyer is still assured of having a product that satisfies his requirements. On the other hand, the contractor could stand to lose any potential profits, and possibly even incur losses due to extensive redesign or repair, should his product fail to meet the standards set. This means that if a substandard product is received, the buyer will not lose anything as provisions in the warranty will protect him from any losses, while the contractor will stand to lose a great deal, and hence will concentrate his efforts to insure that this will not happen, thus protecting himself, and providing a more reliable product. Comparisons of various procurement methods are given in Figure 5-27 (Ref. 5-11).

5.7.2 Warranty Application Criteria

Before a warranty program can be implemented, a decision must be made as to whether or not one should even be used, since in some cases they are not cost-effective. An example of this would be a system which is already part of the inventory, is highly reliable, and can be quickly and cheaply repaired. Obviously such a system would not benefit from a warranty, but rather would increase in cost. Thus it can be seen that there is a need for a set of criteria which will establish when a warranty should be applied. These criteria are generally based on procurement factors, equipment characteristics, and operational factors.

Some of the procurement factors taken into consideration are whether or not the procurement is on a fixed-price basis, if it is competitive, if the quantity of procurement is large enough to make a warranty economical, reputation of the contractor in providing warranty type service, inclusion of an escalation clause in the contract that is applicable to warranty or logistic support costs, availability of multiyear

FACTORS	STANDARD PROCUREMENT AND MAINTENANCE WITHOUT WARRANTY	RIW	RIW/MTBF	LSC/ORGANIC MAINTENANCE
User Risk in Achieving Objectives	High	Moderate	Low	Moderate to high
Contractor Pricing Risk	Low	Moderate	High	Moderate
Administration Difficulty	Low	Moderate	High	Low to moderate
Enforceability Risk	N/A	Moderate	Moderate	Moderate to high
Contractor Reliability Improvement Motivation	Low	Moderate	High	Low to moderate
Commitment Time	N/A	Start of Production	Start of Production	After follow-on operational test
Services Provided	N/A	Depot Maintenance plus no-cost ECPs	Depot maintenance, logistics assets if required, plus no-cost ECPs	Logistics assests if required or equipment ECPs
Logistic Management Difficulty	Low	Moderate	Moderate	Low

Figure 5-27

COMPARISON OF PROCUREMENT METHODS

(Ref. 5-11)

funding services, whether an analysis of warranty price versus organic repair costs is possible, and finally, if the equipment will be in production over a substantial portion of the warranty period.

Equipment criteria will establish such factors as equipment maturity, control of unauthorized maintenance, field testability, whether unit can be marked or labeled to signify existence of warranty coverage, if it is possible to incorporate R&M improvements and changes, and in the case of MTBF or LSC warranties, if an elapsed-time indicator can be installed on the equipment.

Operational criteria consist of a known or predictable use environment, predictability of equipment reliability and maintainability, equipment mission criticality not of the highest level, if failure and usage information can be supplied to the contractor, and if provisions have been made for computing the equipments' MTBF. Figure 5-28 provides a comparison of the applicability of warranty criteria to each of the basic types of programs. The failure of an equipment to meet some of the criteria may be grounds to eliminate the use of a warranty. Not meeting other criteria may only cause special agreements in the warranty contract.

Another major point to be examined before a warranty contract is adopted is the price of contractor (warranty) maintenance as weighed against user maintenance. This is usually accomplished through the development of a LCC model. Use of this type of model will usually determine:

- Baseline life cycle costs without warranty
- Baseline life cycle costs with different warranties
- Optimum warranty duration
- Fair warranty price
- Contingency spare requirements

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Criteria	Importance Rating*		
	RIW	RIW/MTBF	LSC
Procurement			
The procurement is to be on a fixed-price basis.	1	1	1
Multi-year funding for warranty services is available.	1	1	N/A
The procurement is competitive.	2	2	2
Potential contractors have proven capability, experience, and cooperative attitude in providing warranty-type services or LSC commitment.	2	2	2
The procurement quantity is large enough to make warranty economically attractive.	2	2	N/A
Analysis of warranty price versus organic repair costs is possible.	2	2	N/A
An escalation clause is included in the contract that is applicable to warranty or LSC costs.	3	3	3
The equipment will be in production over a substantial portion of the warranty period.	3	1	2
Equipment			
Equipment maturity is at an appropriate level.	1	1	2
Control of unauthorized maintenance can be exercised.	1	1	2
Unit is field-testable.	1	1	N/A
Unit can be properly marked or labeled to signify existence of warranty coverage.	1	1	N/A
Unit is amenable to R&M improvement and changes.	1	1	3
Unit is reasonably self-contained.	2	2	3
Unit can be readily transported to the contractor's facilities.	2	2	N/A
Unit has high level of ruggedization.	2	2	N/A
Unit maintenance is highly complex.	3	3	N/A
An elapsed-time indicator can be installed on the equipment.	3	1	1
Operation			
Use environment is known or predictable.	1	1	1
Equipment operational reliability and maintainability are predictable.	1	1	1
Equipment wartime or peacetime mission criticality is not of the highest level.	1	1	N/A
Equipment has a high operational utilization rate.	2	2	3
Warranty administration can be efficiently accomplished.	2	2	N/A
Duplication of an existing or planned government repair facility is not costly.	2	2	N/A
Unit reliability and usage levels are amenable to warranty maintenance.	2	2	N/A
Operating time is known or predictable.	2	2	3
Operational failure and usage information can be supplied to the contractor.	2	1	3
Backup warranty repair facilities are available.	3	3	N/A
Provision has been made for computing the equipment's MTBF.	N/A	1	1

*1 = Major; 2 = Secondary; 3 = Minor.

Figure 5-28

WARRANTY APPLICATION CRITERIA

Reference 5-11

Once a decision has been made to use a warranty in the procurement of a system, the final and most important consideration as to what provisions to include, must be made. Specific terms of warranty contracts will vary according to the type of warranty being considered, will vary with each different procurement, and according to the individuals involved in the contractual bargaining process. However, due to the fact that all contracts strive for the same goals there does exist some basic provisions common to all. Some of these are:

- Repair all failures - few exclusions allow contractor to evaluate all repairs.
- Material flow - upon failure, a previously agreed upon pipeline spares system must be utilized. This may include such things as repaired unit destination, shipping costs and containers, etc.
- Warranty period - the length of the warranty varies according to the number of units to be serviced and their operating time in order to aid reliability analysis and to maximize potential profits.
- Guaranteed turn-around time - in order to keep system availability as high as possible an equipment replacement time should be specified. This is usually accomplished using a pool of spares.
- Price of warranty - should be based on expected rate of returns of failed equipments and their repair processes (i.e., may be high if extensive equipment burn-in at repair site is used).
- Contingency spares - usually based on agreed turn-around time and number of units in operation.
- MTBF growth - if RIW is used, MTBF growth curve must usually be provided.
- Sealed unit - to recluded unauthorized maintenance, an agreement for sealed units can be used. Also places all responsibility of failure on contractor.

- Reliability proof - for RIW and MTBF guaranteed warranties, a reliability measurement procedure is usually set up.
- Time indicators - establish unit operation time. Aids in realistic calculation of MTBF.
- Supply of data - establishes data requirements for return of failed units.

Other provisions may include obligations regarding design changes, penalties, repair location, spares ownership, etc.

Because of the relative newness of the warranty concept, and the unfamiliarity of industry with the military community, reluctance is generally experienced in considering its use. However, past experience has shown that a properly conducted military warranty program can yield significant benefits in terms of LCC. Further benefits include the incentive provided to the contractor for improved reliability and maintainability, limited maintenance induced failure and reduced complexity of procurement.

5.8 Organizational Considerations

Three separate organizations are involved in the development of Army helicopters. They are:

- Program Manager's Office
- Development Contractor
- Functional Groups In the AVSCOM Command

To provide effective R&M management and control during the development and production effort, close contact must be maintained among these organizations. Figure 5-29 is an overall organizational chart for the Army which highlights the AVSCOM R&M division and its interaction with both Army and outside organizational units. The dotted lines in this figure show outside contractors who are involved with helicopter development or who support the R&M division. Reporting directly to AMC are the Program Managers of the current development efforts.

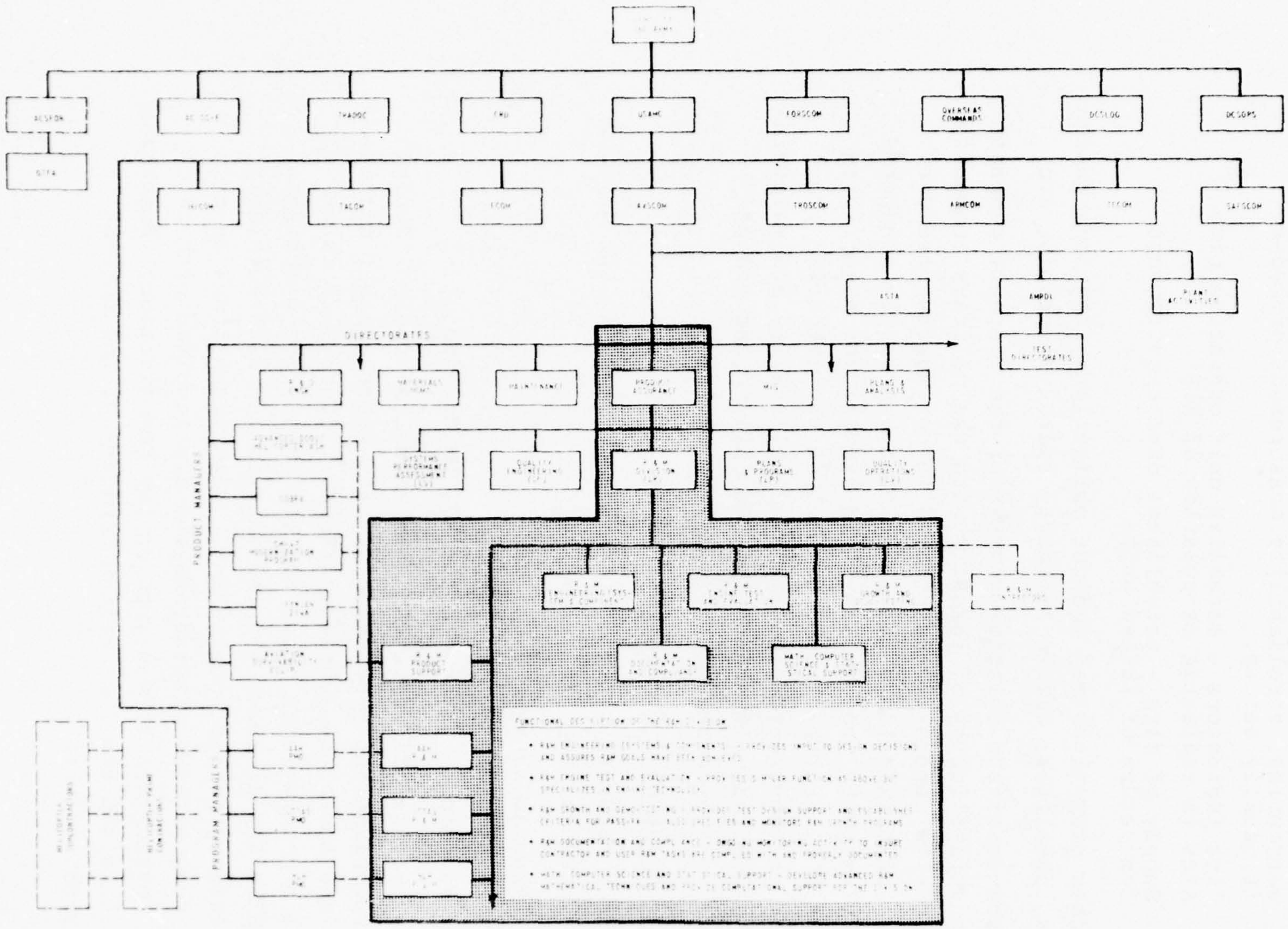

Figure 5-29
ARMY ORGANIZATION

It is the responsibility of the R&M division to:

1. Maintain a staff of personnel with expertise in functional R&M disciplines, such as:

- R&M engineering,
- R&M component engineering (engines, blades, transmissions, etc.)
- R&M growth and demonstration test expertise,
- Mathematics, computer science and statistical support.

2. Provide direct technical support to the Program Manager's office.

R&M program support staff draw upon specialists in the functional areas as is appropriate during the development program. Often, support staff can be directly assigned to programs during a period in which their expertise is required.

Because members of the R&M group must keep abreast of all new developments in their discipline, they also play an educational role by disseminating information on current techniques and methodologies to other groups in the AVSCOM Command, as well as to helicopter contractors.

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ABBREVIATIONS AND ACRONYMS

AAH	Advanced Attack Helicopter
AC	Acquisition Cost
ACSFOR	Assistant Chief of Staff for Force Development
AGE	Auxiliary Ground Equipment
AH-1	Attack Helicopter, Model 1
AMC	Army Materiel Command
AMP	Army Materiel Plan
AMSAV-LR	Army Materiel Systems Aviation - Reliability and Maintainability
APE	Advance Production Engineering
APM	Army Program Management
AQL	Acceptable Quality Level
AQP	Airworthiness Qualification Program
AR	Army Regulation
ASARC	Army Systems Acquisition Review Council
ASOAP	Army Spectro-metric Oil Analysis Program
ATP	Army Training Programs
AVSCOM	Army Aviation Systems Command
BIT	Built-in Test
BITE	Built-in Test Equipment
CDR	Critical Design Review
CDRL	Contract Data Requirement List
CFM	Crash Fact Messages
CFP	Concept, Formulation Package
CH-34	Cargo Helicopter, Model 34
CH-47	Cargo Helicopter, Model 47
COO	Cost of Ownership
CRD	Chief of Research and Development
CTP	Coordinated Test Program
DA	Department of the Army
DAC	Days after Contract
DAT	Development Acceptance Test
DCP	Development Concept Paper
DCSLOG	Deputy Chief of Staff for Logistics
DOD	Department of Defense
DP	Development Plan
DPM	Defense Program Memorandums
DSARC	Defense Systems Acquisition Review Council
DT-I	Development Testing - One
DT-II	Development Testing - Two
DT-III	Development Testing - Three
ECO	Engineering Change Order
EIR	Equipment Improvement Report
EST	Expanded Service Test
ET	Engineering Test

FIT	Fault Isolation Techniques
FM	Field Manuals
FMEA	Failure Modes Effect Analysis
FMECA	Failure Modes Effect and Criticality Analysis
FOD	Foreign Object Damage
FRACA	Failure Reporting Analysis and Corrective Action
FS	Factor of Safety
FTA	Fault Tree Analysis
FMA	Failure Mode Analysis
HLH	Heavy Lift Helicopter
ICAP	Improved Cobra Armament Program
IITRI	Illinois Institute of Technology Research Institute
ILS	Integrated Logistics Support
IPR	In-Process Review
LCC	Life Cycle Cost
LCMM	Life Cycle Management Model
LRIP	Low Rate Initial Production
LRU	Line Replaceable Unit
LSC	Logistic Support Cost
MACI	Military Adapted Commercial Items
MCDT	Mean Corrective Down Time
MDT	Mean Down Time
MEADS	Maintenance Engineering Analysis Data Sheets
MGE	Maintenance Ground Equipment
MIL-HDBK	Military Handbook
MIL-STD	Military Standard
MMH	Maintenance Man Hours
MMH/FLTHR	Maintenance Man Hours per Flight Hour
MN	Materiel Need (was QMR)
MRB	Materiel Review Board
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTBMA	Mean Time Between Maintenance Actions
MTBR	Mean Time Between Repair (Replace)(Removal)
MTBSI	Mean Time Between Safety Incidents
MTTR	Mean Time To Repair
MTTR/R	Mean Time To Remove and Replace
NDT	Non-Destructive Testing
NS	Non-Standard
OH-6	Operational Helicopter, Model 1
OH-58	Observation Helicopter, Model 58
O & M	Operating and Maintenance
OMA	Operation and Maintenance Army
OSD	Office of Secretary of Defense
OT-1	Operational Testing - One
OT-II	Operational Testing - Two
OT-III	Operational Testing - Three
OTEA	Operational Test and Evaluation Agency

PAG	Part Advisory Group
PAM	Pamphlet
PAP	Product Assurance Plan
PCP	Project Change Proposals
PDR	Repliminary Design Review
PDT	Preventive Downtime
PEMA	Procurements Equipment and Missiles Army
PEP	Procurement Engineering and Planning
PERT	Program Evaluation and Review Technique
PIP	Product Improvement Program
PM	Preventive Maintenance
PSI	Pounds per Square Inch
PSN	Probability-Stress-No. of Cycles (Fatigue Analysis)
QA	Quality Assurance
QC	Quality Control
QMA	Qualitation Material Approach
QMR	Qualitation Material Requirement
RADC	Rome (N.Y.) Air Development Center
RAMMIT	Reliability and Maintainability Management Improvement Techniques
R/D	Research and Development
RDAT	Research and Development Acceptance Test
RDTE	Research and Development Tests and Engineering
RFP	Request for Proposal
RIW	Reliability Improvement Warranty
R&M	Reliability and Maintainability
ROC	Required Operational Capability
SDP	System Development Plan
SEM	Scanning Electron Microscope
SHP	Shaft Horsepower
SN	Refers to Stress-Number of Cycles
SOW	Statement of Work
SSAC	Source Selection Advisory Council
SSEB	Source Selection Evaluation Board
SSI	Stress-Strength-Interference (Probabilistic Design)
SST	Stress-Strength-Time-Theory
TAERS	The Army Equipment Record System
TAMMS	The Army Maintenance Management System
TBO	Time Between Overhaul
TC	Type Classification
TDP	Technical Data Package
TH-55	Trainer Helicopter, Model 55
TM	Technical Manual
TMDE	Test Measurement and Diagnostic Equipment
TOE	Tables of Organizations and Equipment
UER	Unsatisfactory Equipment Report
UH-1	Utility Helicopter, Model 1
UTTAS	Utility Tactical Transport Aircraft System

Appendix A

LIFE CYCLE MANAGEMENT MODEL FOR

MAJOR ARMY SYSTEMS

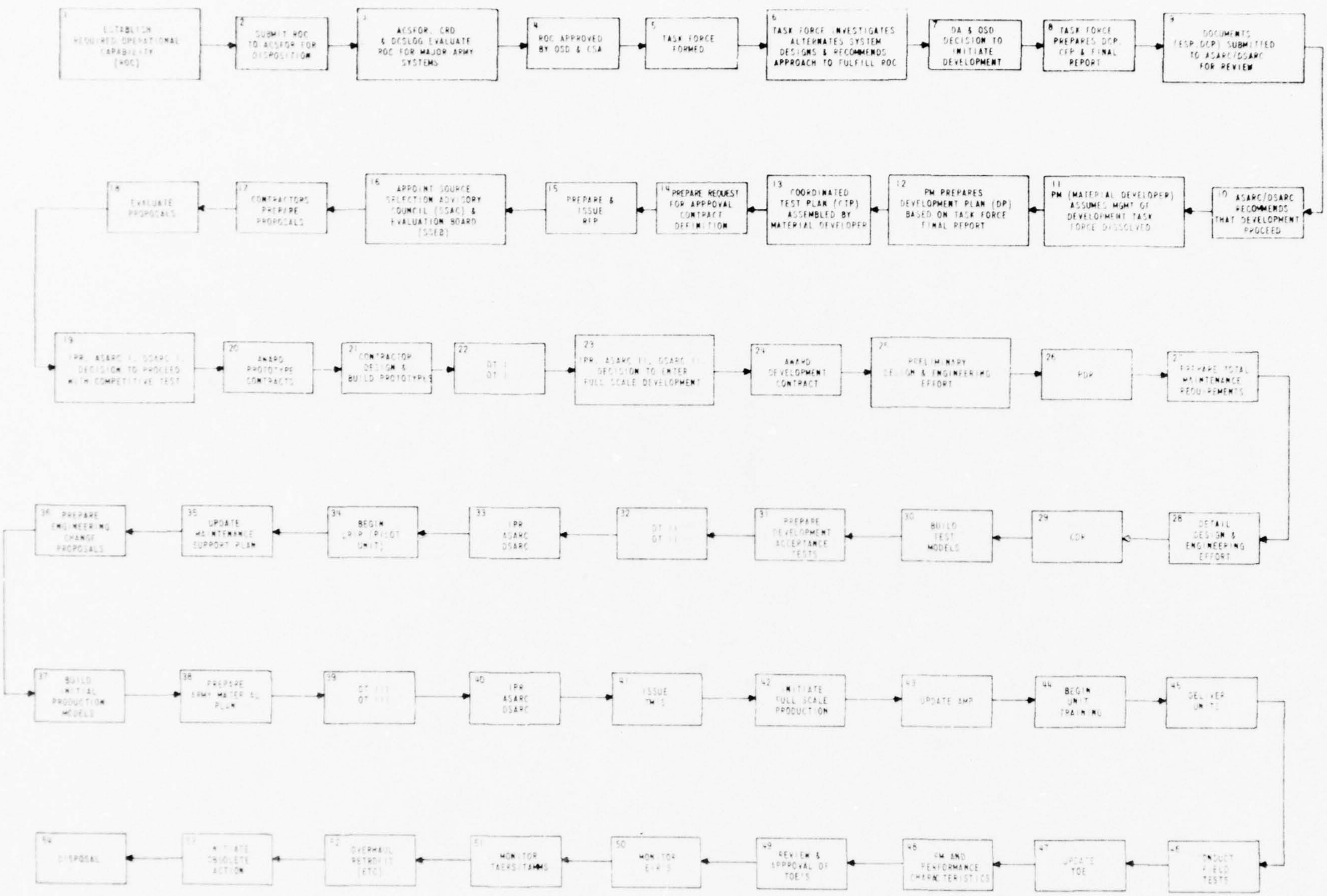

Figure A-1 LIFE CYCLE MANAGEMENT MODEL FOR MAJOR ARMY SYSTEMS
(SIMPLIFIED FLOW CHART)

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Note: This flow chart presents in simplified form, the life cycle management model for major army systems. The criteria for determining whether a system is major is based on the following:

- Potential of system on operational capability
- Level of interest
- Resource impact
- Complexity and risks
- Relationship to other programs

DESCRIPTIONS OF LIFE CYCLE MANAGEMENT
MODEL FOR MAJOR ARMY SYSTEMS

BLOCK NUMBER	DESCRIPTION
1 & 2 *	Required Operational Capability (ROC) is a description of a material need brought about by current material's obsolescence, definition of new mission requirements or the emergence of a technological opportunity. The ROC should contain the minimum essential operational, technical and cost information required for HQ DA decision to initiate development for a new system. The ROC can be originated by anyone. The originator of the ROC will submit it to the Assistant Chief of Staff for Force Development (ACSFOR) for disposition. ACSFOR may require additional definition by the originator or by the most appropriate Army agency.
3	ACSFOR in coordination with the Chief of Research and Development (CRD) and the Deputy Chief of Staff for Logistics (DCSLOG) will evaluate the ROC and recommend approval (or disapproval) along with recommended implementing instructions for the task force.
4	ROC approved by Chief of Staff Army (CSA) and the Office of the Secretary of Defense (OSD).
5	After approval of the ROC, a special task force under the supervision of ACSFOR will be assembled. The task force will be composed of:

1. Director--best qualified officer,
2. Project Manager Designer--the prospective PM,
3. User--Major Operational Command,
4. Material Developer--AMC, Chief of Engineers or other,
5. Combat Developer--USACDC, STRATCOM or other,
6. Trainer--schools and centers
7. Resource Programmer--HQ DA staff

* Numbers refer to block numbers on Fig. A-1

DESCRIPTIONS OF LIFE CYCLE MANAGEMENT
MODEL FOR MAJOR ARMY SYSTEMS

BLOCK NUMBER	DESCRIPTION
8 & 9	The task force produces 3 major documents, namely, the Development Concept Paper (DCP), the Concept Formulation Package (CFP) and the Final Report. The DCP is the major document for discussion at an Army Systems Acquisition Review Council (ASARC) and Defense Systems Acquisition Review Council (DSARC) review. The DCP contains: (1) nature of program, (2) cost, schedule, performance thresholds, (3) system/program alternatives. The DCP is an agreement between the OSD and the Army which records the final decision of the Secretary of Defense. The CFP supports the DCP and consists of trade-off analyses, best technical approach and cost & operational effectiveness. The final report of the task force includes: (1) system summary, (2) system requirements. (3) discussion of alternatives, (4) plan for system development, (5) technical portion of the Request for Proposal, (RFP) (6) financial and procurement plan. The final report will be turned over to the prospective Project Manager (PM) for his use and as input to the Development Plan (DP).
10 & 11	After evaluating the DCP, ASARC/DSARC recommends that development proceed. The task force is dissolved by ASARC after completion of the required documents and after the PM assumes management responsibility.
12 & 13	The mjterial developer prepares the development plan (DP). The DP is the controlling document for the material development effort and will be refined and updated periodically. Both the ROC and DCP are incorporated into the DP. The development plan contains provisions for Coordinated Test Program. (CTP).
14 & 15	The material developer prepares a request for approval of contract definition for submission to HQ DA (ACSFOR). Upon approval by HQ DA, the material developer prepares and issues the RFP.

DESCRIPTIONS OF LIFE CYCLE MANAGEMENT
MODEL FOR MAJOR ARMY SYSTEMS

BLOCK NUMBER	DESCRIPTION
16	The Source Slsection Advisory Council (SSAC) is appointed by the Secretary of the Army composed of senior military and civilian personnel who act as advisors during the source selection process. The SSAC appoints the chairman and establishes the composition of the Source Selection Evaluation Board (SSEB).
17	Based on the RFP documents, contractors will prepare proposals showing how they intend to meet all requirements.
18 & 19	Contractor proposals are evaluated for technical adequacy, cost and schedule. Based on the results of these evaluations, ASARC/DSARC makes the decision to proceed with competitive evaluations.
20 & 21	Following selection of one or more contractors based on proposal evaluations, prototype contracts are awarded and contractors proceed to design and built prototypes.
22 & 23	Upon delivery of the prototype, initial development tests (DT) and operational tests (OT) will be conducted to demonstrate significant military and technical characteristics. These tests are limited in scope but are designed to reduce acquisition risks and support subsequent decisions. Based on the results of DT-I/OT-I, ASARC/DSARC provides the decision to proceed with full scale development.
24 & 25	Following the decision to proceed, a development contract (or contracts) is awarded, followed by the preliminary design and engineering effort.
26	A Preliminary Design Review (PDR) is usually held to assess the progress of the design. Design reviews are held between contractor and Army personnel

DESCRIPTIONS OF LIFE CYCLE MANAGEMENT

MODEL FOR MAJOR ARMY SYSTEMS

BLOCK NUMBER	DESCRIPTION
27, 28, 29, 30 & 31	Following PDR, the contractor proceeds with detail design activities followed by a Critical Design Review (CDR) preceeding the build up of test models. During this period, the total maintenance requirements are prepared as are the Development Acceptance Tests (DAT).
32, 33 & 34	Delivery of development models to the Army precipitates the conduct of further development and operational testin (DTII/OTII). If the results of these tests are favorable, DSARC/ASARC provides the devision to enter Low Rate Initial Production (LRIP).
35 & 36	Based on the results of OTII/DTII testing, the maintenance support plan may be revised to incorporate increased or decreased support requirements and to prepare maintenance literature. Engineering change proposals are prepared to establish change control for the early production period.
37 & 38	In parallel with the build up of initial production models, the Army Material Plan (AMP) is prepared. The purpose of this plan is to maintain balanced modern inventories and meet the total dollar requirements of the PEMA appropriation.
39 & 40	DT III testing begins when the first production models become available. DT III tests verify the successful transition from an engineering development model to a production item which meets the specifications prescribed and quantity production processes. DT III is an intensive major field test to verify the organization and doctrine, logistics, maintenance support, tactics and training are adequate. Based on these results, ASARC/DSARC provides the decision to proceed into full scale production.
41 & 42	The issuance of Technical Manuals (TM) (for operation and maintenance) occurs during this period and coincides with the initiation of full scale production.

DESCRIPTIONS OF LIFE CYCLE MANAGEMENT
MODELS FOR MAJOR ARMY SYSTEMS

BLOCK NUMBER	DESCRIPTION
43, 44, 45 & 46	During the period immediately following the initiation of full scale production, the following activities take place: (1) The Army Material Plan is updated, (2) unit training begins and progresses in accordance with Army Training Programs (ATP) prepared by training schools, (3) units are delivered to field sites, and (4) field tests are conducted.
47, 48, & 49	Following the conduct of user (field) tests, the Table of Organizations and Equipment (TOE), the Field Manuals (FM) and performance characteristics are revised and approved.
50 & 51	Throughout the deployment phase, Equipment Improvement Reports (EIR) and maintenance data and reports are monitored and data collected to track actual system performance.
52	Included here are overhauls due to normal wearout, engineering changes and modifications which occur as a result of change proposals, etc.
53 & 54	As newer, more modern systems are conceived and developed for inclusion into the inventory, action to remove the older system from the inventory is initiated, eventually leading to disposal.

APPENDIX B

R&M DOCUMENTS

AMCP-702-21, PRODUCT ASSURANCE DISCIPLINES FOR THE 70's, 1971.

Provides an overview of the various technical skills required for the AMC Product Assurance System during the 1970's and demonstrates the specific skill requirements by relating them to the functions necessary for the conduct of the program. Prescribes required system support disciplines at mission levels, including: (a) R/M Division-Component reliability, prediction and apportionment, failures mode and effect analysis, tolerance evaluation, stress/strength analysis, R/M demonstration and tests, and competence and responsibility; (b) Quality Engineering Division; (c) System Performance Assessment Division - collective life cycle data, product assessment and system planning, R growth management information system, controlled data collection system, support new program justifications, and R improvement of selected equipment; (d) Quality Operations Division; (e) Plans and Program Analysis Division; and (f) Product Assurance Operations.

AMCP-706-132, MAINTENANCE ENGINEERING TECHNIQUES HANDBOOK, 1974.

Covers Maintenance Engineering and how it affects the design of a system throughout its life cycle. Provides techniques for making decisions for the optimum level of maintainability with minimal tradeoffs. Other concepts covered are methods of data collection and decision making, and management and control of the Maintenance Engineering process.

AMCP-706-134, ENGINEERING DESIGN HANDBOOK (Maintainability Guide for Design), 1970.

Describes and covers the Maintenance Problem, and shows how to go about reducing it in future designs. This is accomplished in five parts as follows: (a) describes the extent of the Maintenance Problem in terms of expenditure of money, men and material; (b) presents maintainability objectives, principles and procedures; (c) describes the nature of the Maintenance Problem in terms of the conditions under which weapon systems must be operated and maintained, from the logistical, human and environmental points of view; (d) deals with design considerations that have general applicability to all types of Army material; and (e) present design considerations applicable to specific types of Army material. An appendix presents a tabulation of applicable military specifications, standards and publications.

AMCP-706-191, ENGINEERING DESIGN HANDBOOK (System Analysis and Cost Effectiveness), 1971.

Covers System Analysis and Cost Effectiveness and aims its discussions at technical, scientific, management, and administrative personnel. Gives the information necessary to make decisions concerning life cycle cost, system effectiveness (availability, dependability, capability), or technical feasibility of a system or equipment at any phase in its life cycle. The topics covered are: (a) an introduction to the concept of system analysis and cost effectiveness; (b) a basic framework, or general methodological approach, for conducting and reviewing cost effectiveness of system analysis studies; (c) a set of techniques used for performing cost effectiveness and system analysis studies; (e) a review of basic mathematical and statistical concepts that underlie the scientific approach in the system analysis, cost effectiveness process.

AR 5-5, THE ARMY STUDY SYSTEM, 1971.

Establishes the Army Study System (TASS), assigns functional responsibilities and prescribes procedures to be followed in contracting for operations research and management studies. Develops the Army Study Advisory Committee (ASAC), The Army Study Program (TASP), and Study Advisory Groups (SAG). Defines responsibilities of Contract Studies, including Management and Operations Research (application of objective, analytical thinking, supported by selected research tools, to the analysis fo complex problems and related implications). Prescribes responsibilities and procedures for initiating, preparing, monitoring, and processing studies directed by the Chief of Staff, Army (CofSA) or Secretary of the Army (SA), including directed studies which are accomplished partially or entirely by contract. Provides formats for initiating studies.

AR 11-26, VALUE ENGINEERING, 1968.

Directed toward analyzing the function of Army Sections for the purpose of achieving the required task at the lowest total cost of effective ownership, consistent with requirements for performance, reliability, quality, and maintainability. Prescribes obtainment of total value improvement in research, design, development, test and evaluation, production, procurement, quality assurance, construction, supply, transportation, maintenance, personnel, training, storage and disposition programs through the use of value engineering principles and techniques.

AR 15-14, SYSTEMS ACQUISITION REVIEW COUNCIL PROCEDURES, 1973.

Provides DA instructions and establishes procedures for Army System Acquisition Review Councils (ASARC) and participation in Defense Systems Acquisition Review Councils (DSARC) for acquiring major Army systems. Reviews programs designated by SECDEF for (a) dollar value; (b) national urgency; and (c) recommendations by Secreatry of the Army of OSD officials. Defines phases of acquisition (conceptual, validation, full-scale development, and production/deployment), which are referred to as milestones. Prescribes checklists for Milestone Reviews.

AR 70-1, ARMY RESEARCH AND DEVELOPMENT, 1973.

Seeks the timely development of DA weapons, equipment, and systems capable of being effectively manned, and superior to those of any potential enemy, and any environment, and under all conditions of war. Prescribes (a) Policy and principles for conducting research and development; (b) Development options; (c) Priorities; (d) RDTE facilities; and (e) Responsibilities. Defines process for research, development, test and evaluation (RDTE). Establishes policy and objectives of (1) Technology Base - Research and Exploratory Development, (2) System Development - Advanced Engineering and Operation Systems Development, and (3) establishes assignment of R&D programs. Graphically presents Levels of Decision Authority; Relationships between DA Requirements Documents, LCMM Phases, and RDTE; and Responsibilities for conducting R&D Programs.

AR 70-10, TEST AND EVALUATION DURING DEVELOPMENT AND ACQUISITION OF MATERIEL, 1971.

Prescribes the objectives, concepts, responsibilities, policies, and major tests which apply to the testing and evaluation leading to type classification of Army materiel. The portion of the life cycle covered by this regulation starts with the initial preparation of the Coordinated Test Program in the concept formation phase and ends with the successful completion of the production validation process. Provides general policies for agency's testing and evaluation. Defines responsibilities of Army Staff and Contractors Agencies. Categorizes test and evaluation activities. (Including R/M Demonstration - conducted on development prototypes or production models to provide for the demonstration of R/M requirements as expressed in the SDR, QMR, or Materiel Needs documents and required by AR 705-50. The major product of this test is the determination of major component service lives. Time Between Overhaul priority will be provided for operation, component inspection and overhaul, and controlled component shipping.) Prescribes test directives, policy, design, and reports.

AR 70-27, DEVELOPMENT PLAN/DEVELOPMENT CONCEPT PAPER/PROGRAM MEMORANDUM, 1973.

Prescribes policy, procedures, and content for Development Plans (DP) and Army Program Memoranda (APM), and defines responsibilities for processing OSD Development Concept Papers (DCP) and OSD-directed Defense Program Memoranda (DPM). Describes the connections and relationships among DP, DCP, DPM, APM and the program reviews by the Defense System Acquisition Review Council (ASARC). Applies to both developmental and non-developmental programs undertaken to satisfy approved Army materiel requirements. Establishes format for DP as: (1) Summary, (2) Requirements & Analysis; (3) Development Plans - technical, management, financial, facilities and resources, and advance procurement; (4) Coordinated Test Programs; (5) Plan for Personnel and Training Requirements; and (6) Plan for Logistics Support - special needs, estimates of life cycle support costs and identification of requirements.

AR 70-37, CONFIGURATION MANAGEMENT, 1969.

Applies technical and administrative direction and surveillance to (a) identify and document the functional and physical characteristics of a configuration item, (b) control changes to those characteristics, and (c) record and report change processing and implementation status. Assists management in achieving, at the lowest life cycle cost, the required performance, operational efficiency, logistic support and readiness of configuration items (CI). Allows the maximum degree of design and development latitude, yet introduces the degree and depth of configuration control necessary for production support, product assurance and test. Attains maximum efficiency in management of configuration changes with respect to their necessity, benefits, cost, timing and implementation. Attains the optimum degree of uniformity and reports all interfaces. Applies to all CI's procured by the Army or obtained through an agreement between Army in-house activities.

AR 70-38, RESEARCH, DEVELOPMENT, TEST, AND EVALUATION OF MATERIEL FOR EXTREME CLIMATIC CONDITIONS, 1969.

Prescribes policies, responsibilities, and planning guidance for realistic consideration of climatic conditions in the research, development, test and evaluation (RDTE) of material used in combat by the DA. Categories are designated to provide guidance in the preparation of Qualitative Materiel Development Objectives, Qualitative Materiel Requirements, Small Development Requirements, Operational Capability Objectives, Advanced Development Objectives and other documents covering RDTE and procurement of Army materiel.

AR 71-1, ARMY COMBAT DEVELOPMENTS, 1971.

Strives to increase the combat effectiveness of the Army as rapidly as possible at realistic costs by the orderly development of new or improved doctrine, organization, materiel objectives and requirements, and by the early integration of the resultant products into the Army. Records combat development objectives, major studies, field experiments, troop tests, combat and field evaluations, and qualitative materiel objectives and requirements in a DA publication - Combat Development Objectives Guide. Provides the technical, economic, and military basis for a decision to initiate engineering development through Concept Formulation (AR 11-25). Prescribes procedures for the rapid response of the DA to commanders' urgent requirements for new or nonstandard materiel, organizations, and doctrine to support current combat, active or semiactive operations. Lists requirements for acquisition of nonstandard item for evaluation.

AR 71-3, USER FIELD TESTS, EXPERIMENTS, AND EVALUATIONS, 1970.

Outlines objectives, policies, responsibilities and procedures for conduct of user field tests, experiments and evaluations, which include troop tests, confirmatory tests, field evaluations, and combat evaluations. Following completion of the development and production acceptance testing cycle, the troop tests, experiments and evaluations described in this regulation established the performance capabilities of selected items of Army equipment in the hands of the user and the workability and effectiveness of organizational concepts, doctrine, tactics and techniques and tables or organization duty positions.

AR 71-5, INTRODUCTION OF NEW OR MODIFIED SYSTEMS/EQUIPMENT, 1969.

Establishes the management system by which trained personnel are provided to operate and maintain new or modified Army managed systems/equipment. These personnel must be available prior to the introduction of the systems/equipment into the Army inventory as an asset for testing or troop issue. Included are tri-service systems/equipment for which the Army has management responsibility. Presents the DA Training and Support Committee which is concerned with scheduled delivery of new systems/equipment or planned major modifications.

AR 95-5, AIRCRAFT ACCIDENT PREVENTION, INVESTIGATION, AND REPORTING, 1966.

Applies to all Army activities engaged in the utilization, operation, and maintenance of Army aircraft.

PART I - Prevention - contains policies and guidance for establishing and developing a sound accident prevention program at all levels of command. Prescribes the optimum conservation of aviation personnel and materiel resources by minimizing losses due to accidents. Establishes an Army Aviation Safety Program, including a safety council, command and staff, training, investigations, and periodic reviews.

PART II - Investigation - contains basic and technical information and procedures for conducting Army aircraft accident investigation. Determines accident cause factors. Assembles information for recommendations for preventing future accidents. Provides statistical data used to evaluate the overall Army accident experience so that required corrective action can be taken. Prescribes responsibility, collateral investigative procedures, techniques of investigation (varies, depending on the type of occurrence being investigated and the number of officers appointed to the board), and medical factors.

PART III - Reporting - contains techniques and guidance for the preparation and organization of accident reports available through normal AG publications supply channels. Defines reporting procedures; instructions for completion on crash facts message, RCS CSGPA-459(*); guidelines for completion of DA form 2397 series (Technical Report of U.S. Army Aircraft Accident), RCS CSFOR-5 (R2); and the assembly of accident folders.

Implements the (1) Crash Plan Guide, (2) Operational Hazard Report, (3) Description of Fractures and Damaging Stresses, (4) General Checklist for Aircraft Accident Reports, (5) Aviation Safety Planning Guide, and (6) Accident Prevention Guide.

AR 385-16, SYSTEM SAFETY, 1972.

Prescribes concepts, policies, responsibilities and requirements for the Army Safety Program for systems, and establishes essential life cycle system safety engineering and management tasks. Assures: (a) Maximum safety consistent with mission requirements is designed into systems; (b) Hazards associated with systems are identified early in the life cycle and either eliminated or controlled to an acceptance level, (c) Minimum risk is involved in the acceptance and use of new material and new production and testing techniques, (d) Retrofit actions required to improve safety are minimized through the timely inclusion of safety factors during the development and acquisition of systems, (e) Historical safety data generated by similar system programs are considered and used where

appropriate, and (f) Consideration is given to safety and ease of demilitarization and disposal of any hazardous material associated with systems. Applies to all commands, installations, or activities that develop, acquire, use, or dispose of Army systems.

AR 385-40, ACCIDENT REPORTING AND RECORDS, 1969.

Prescribes definitions, procedures, and requirements for investigating, reporting, recording, and summarizing Army accidents referred to in AR 385-10, including the maintenance and use of records and cause data. Defines general terms and types of Army accidents and incidents. Includes methods for preparing and processing forms for Army Aircraft Accidents, Nuclear Weapon Accidents and Incidents, Nuclear Reactor Accidents and Incidents, Chemical and Biological Accidents and Incidents, and Training and Troop Movement Accidents. Reports control symbols DD-SD(AR)730, CSGPA-147(R3), CSGPA-459, CSGPA-646(R2), CSGPA-686, CSFOR-5(R1), CSFOR-68, CSFOR-142(MIN), LABOR-1014, and AEC-1006(MIN). Includes examples of completed reports.

AR 700-35, PRODUCT IMPROVEMENT OF MATERIEL, 1971.

Establishes policy and assigns responsibilities for product improvement of Army material. Provides practical criteria for determining which appropriation will be used to finance improvements. Deals mainly with material changes that are intended to improve availability, reliability, maintainability, and safety or reduce production or logistics support cost as part of the procedure methods for the acquisition of Product Improvement Programs and Funding. Includes questionnaire to be used by item managers in determining whether a proposed product improvement is developmental in nature or is an adjunct of the production or operational phase of an item's life cycle.

AR 700-47, DEFENSE STANDARDIZATION PROGRAM, 1967.

This regulation establishes standardization policy, procedures, and guidance in support of design, development, procurement, production, inspection, supply, maintenance, and disposal of equipments and supplies; provides for management practices by which the records of the engineering determinations affecting standardization are established, effectively integrated with current information and updated as required, utilized to reduce the variety of similar items, and utilized as the basis for the timely development of needed standards. The objectives of this regulation strive to (a) improve operational readiness; (b) conserve human, natural, and materiel resources, and (c) enhance interchangeability and R&M of military equipments and supplies.

AR 700-51, <u>ARMY DATA MANAGEMENT PROGRAM</u>, 1973.

Establishes policies, assigns responsibilities and prescribes procedures for DA implementation of DODI 5010.12 and the interim implementation of DODI 5010.29. Provides a management system for generating cost reductions in support of Cost Reduction Area 3 (Table 2-1, AR 11-20). Applies to all elements of the DA which require, prepare, or purchase data. Prescribes Army activities having a need for data from a contractor or from other services by MIPR to (a) Develop and maintain an effective Data Management Program (DMP) to identify and justify the minimum data required for each item of material then control procurement, preparation, acceptance, delivery, storage, retreival, review, updating, interchange, and distribution of all data throughout the life cycle of the materiel; (b) Develop and maintain systems for management and control of data through all phases, from determination; (c) Implement the DMP and technical documentation plans. Includes information in regard to reducing the cost of data acquisition and maintenance, and guidance for insuring adequate design disclosure in the acquisition of data.

AR 700-90, <u>ARMY INDUSTRIAL PREPAREDNESS PROGRAM (AIPP)</u>, 1973.

Consists of (a) the Production Base Support Program financed by procurement of equipment and missiles, and (b) the industrial preparedness operations which sustain the industrial production base financed by the BP728011 of the operation and maintenance. Insures that the facilities and required industrial plant equipment are either on hand or attainable within an acceptable time frame. Founded on a combination of inventory on hand and a responsive and committed production capability. Prescribes Army Industrial Preparedness Planning. Establishes the Army Production Base Support Program in terms of policies and procedures, provision of industrial facilities, production engineering, layaway and redistribution of industrial facilities, and policies and instructions for preparation and submission of projects. Prescribes policies and procedures governing real estate acquisition and disposal as well as the AIPP activities involving construction, conversion, modernization, real property maintenance, and disposal of real property other than real estate. Prescribes regulations for the management and retention of industrial plant for which the Army is responsible in DA industrial production installations, arsenals, and contractor-owned or operated plants.

AR 702-1, REPORTING UNSATISFACTORY NEWLY PROCURED AND CONTRACTOR MAINTAINED MATERIEL, 1971.

Applies to all U.S. Army installations, elements, or activities receiving or storing new materiel or materiel maintained, repaired, or overhauled by an industrial contractor (also that which is found to be unsatisfactory at time of receipt from sources other than procurement; or during storage or maintenance operations. Seeks to provide (a) pertinent quality and reliability information to effect prompt corrective action with respect to unsatisfactory materiel; (b) prompt and effective disposition instructions for unsatisfactory materiel; (c) management indicators as to the effectiveness of a contractor's performance and the Government's Procurement Quality Assurance operations; and (d) improvement of the quality and reliability of Army materiel. Prescribes methods concerning the Unsatisfactory Materiel Report (UMR) by means of investigation, definition, validation, return and labeling. (DD Form 1686)

AR 702-3, ARMY MATERIEL RELIABILITY, AVAILABILITY, AND MAINTAINABILITY, 1973.

Provides Regulations and General Policies for the establishment of the reliability, availability and maintainability (RAM) of systems and facilities developed, produced, maintained, procured, or modified for Army use. Establishes RAM characteristics specified for materiel design and assessed throughout its life cycle. Clarifies the interrelationship between RAM technical and operational performance characteristics, as well as between RAM characteristics and integrated logistics support.

AR 750-1, MAINTENANCE CONCEPTS, 1967.

Seeks to assure that Army materiel is sustained in a ready condition, consistent with economy, to fulfill its designed purpose in the areas of Materiel Development, Reproduction Planning and Production, and Maintenance Operations. Establishes the Maintenance Support Plan - setting forth, in detail, engineered standards for establishing acceptable maintenance downtime and optimum operating time ratios in relation to total availability time. This plan is to be the basis for the development of required maintenance support materiel and publications. Defines areas of (a) maintenance concept, (b) research and development item review, (c) standardization, (d) reliability and maintainability, (e) materiel tests, (f) production engineering, (g) contractual considerations, (h) allocation and allowances for repair parts, tools and support equipment, (i) categories and principles of maintenance, (j) contract maintenance, (k) inspection, and (l) production and delivery.

AR 750-37, SAMPLE DATA COLLECTION THE ARMY MAINTENANCE MANAGEMENT SYSTEM (TAMMS), 1971.

Applies to all Army units and activities responsible for recording and reporting equipment performance data including equipment proponents responsible for life cycle mangement of equipment for which sample data will be obtained. Seeks to (a) preclude the receipt of gross amounts of TAMMS data at the national level; (b) provide for additional improvement of TAMMS; (c) provide a means for collecting under controlled conditions, valid data required to assess the performance effectiveness of Army materiel; (d) improve quality, accuracy, and timely submission of data used in product improvements and performance assessments; (e) evaluate the adequacy of supply and maintenance support; (f) reduce the administrative process at data processing installation (DPI) level and higher that are necessary to obtain maintenance management information; and (g) reduce the volume of maintenance management data to a level that is consistent with the Army's resources to manage it.

AR 750-43, TEST MEASUREMENT, AND DIAGNOSTIC EQUIPMENT (TMDE), 1971.

Seeks to (a) manage the development, test and evaluation, procurement, production, distribution and utilization of TMDE and prognostic equipment; (b) insure the capability of performing timely and accurate item/module/component/assembly malfunction identification, isolation, diagnosis, and failure prediction; (c) optimize cost effectiveness; (d) eliminate unnecessary module/component/assembly removal/exchange/replacement through employment of TMDE; (e) expedite the development of automatic test equipment and prognostic/prediction devices (PPD), preferably multipurpose; and (f) reduce the Army's TMDE inventory by eliminating unnecessary proliferation and duplication. Prescribes TMDE configurations and authorizations by the establishment of the DA Time Advisory Group, staff visits, and reports.

AVSCOM-PAM-702-1, CRITICAL PARTS MANAGEMENT, 1974.

Serves as a mangement tool and a suggested guide for implementation of a production Critical Parts Management Program by project and product managers, depots, subordinate activities, and is related to prime contractors and their supplies. Establishes a preventive rather than a corrective approach to critical characteristics in order to detect, identify and correct systems shortcomings. Prescribes requirements for (a) Design and Production; (b) Critical Parts Interface with Reliability; (c) Plant Activity; (d) Field Operations; (e) Depot Operations; and (f) Feedback Cycle. Includes suggested contractual language for critical parts control.

DRSAU-TR-76-11, RELIABILITY PREDICTION, ASSESSMENT AND GROWTH, 1976.

The report presents a detailed step by step procedure to: (a) evaluate the magnitudes of defects induced by a manufacturing process; (b) estimate the efficiency of manufacturing inspections; (c) compute the reliability of systems and components leaving production. Also, a preliminary data base is provided containing gross defect rates and inspection efficiency factors were collected from on-site visits to helicopter manufacturers; interviews with contractors, subcontractors and Army personnel, and collection and review of historical data. Examples are given to illustrate how the procedure is used, and how it allows assessment and control of reliability growth.

MIL-HDBK-217A, RELIABILITY STRESS AND FAILURE RATE DATA FOR ELECTRONIC EQUIPMENT, 1965.

This handbook provides essential failure rate data for electronic parts and indicates how MIL-STD-756 may be implemented using this data. The handbook was designed to improve prediction accuracy. Application K factors are included to account for the severity of the use environment.

MIL-HDBK-472, MAINTAINABILITY PREDICTION, 1966.

Provides information on current maintainability prediction procedures. Provides valuable information and guidance to personnel concerned with the design, development, and production of equipment and systems requiring a high order of maintainability. Includes procedures dependent on the use of recorded R/M data and experience which have been obtained from comparable systems and components under similar conditions of use and operation. Prescribes four Maintainability Prediction Procedures. Procedure I - system downtime of airborne electronic and electro-mechanical systems involving modular replacement at the flight-line. Procedure II - methods and techniques used to predict Corrective, Preventive and Active Maintenance parameters. Procedure III - method of performing a maintainability prediction of ground electronic systems and equipment by utilizing the basic principles of random sampling. Procedure IV - historical experience, subjective evaluation, expert judgment, and selective measurements for predicting the downtime of a system/equipment; uses existing data to the extent available; provides an orderly process by which the prediction can be made and integrates preventive and corrective maintenance; task times to perform various maintenance actions are estimated and then combined to predict overall system/equipment maintainability. Procedures I and III are solely applicable to electronic systems and equipment. Procedures II and IV can be used for all systems and equipments. (In applying Procedure II to non-electronic equipments, the appropriate task times must be estimated.)

MIL-Q-9858A, QUALITY PROGRAM REQUIREMENTS, 1963.

Establishes a quality program by the contractor to assure compliance with the requirements of the contract. Prescribes requirements for (a) Management; (b) Facilities and Standards; (c) Purchasing Controls; (d) Manufacturing Control; and (e) Coordinated Government/Contractor Actions. Applies to all supplies (including equipments, subsystems, and systems) or services when referenced in the item specification, contract or order.

MIL-STD-470, MAINTAINABILITY PROGRAM REQUIREMENTS FOR SYSTEMS AND EQUIPMENT, 1966.

Provides requirements for establishing a maintainability program and guidelines for the preparation of a maintainability program plan. Its coverage applies to the development of all systems and equipment subject to contract definition, and to the development of other systems and equipment when specified.

MIL-STD-471, MAINTAINABILITY DEMONSTRATION, 1970.

Provides procedures and test plans for evaluating maintainability with respect to quantitative requirements. Also provides for qualitative assessment of various support factors related to item downtime. Can be used to demonstrate maintainability at any level (system, subsystem, equipment, etc.) and at any level of maintenance under any defined set of maintenance conditions. Includes standard procedures for demonstration of maintainability and a number of test plans.

MIL-STD-721A, DEFINITION OF TERMS FOR RELIABILITY ENGINEERING, 1962.

Provides standard definitions for terms most commonly used in reliability engineering.

MIL-STD-756A, RELIABILITY PREDICTION, 1963.

Establishes uniform procedures for predicting the qualitative reliability of Aircraft, Missiles, Satellites, Electronic Equipment and their subsystems throughout the development phases to reveal design weaknesses and to form a basis for apportionment of reliability requirements to the various subdivisions of the product.

MIL-STD-781B, RELIABILITY TESTS: EXPONENTIAL DISTRIBUTION, 1967.

Outlines test levels and test plans for reliablity qualification (demonstration), reliability production acceptance (sampling) tests, and for longevity tests. (The test plans are based upon the exponential, or Poisson distribution, and are intended for the testing of equipment.) Provides uniformity in R testing by: (a) Facilitating the preparation of Military Specs and Standards through the establishment of standard test levels and test plans; (b) Restricting the variety of reliability tests so that those conducting tests can establish facilities; (c) Facilitating the determination of more realisitic correlation factors between test and operational reliability; and (d) Facilitating the direct comparison of MTBF test results through the establishment of uniform test levels and plans. Includes graphic examples and examples of records and reports.

MIL-STD-785, REQUIREMENTS FOR RELIABILITY PROGRAM, 1965.

Establishes unifrom criteria for reliability programs and provides guidelines for the preparation of reliability program plans. Lists detailed requirements as Program Elements including: (a) R organization; (b) Management and Control; (c) Program Review; (d) Development and Qualification Testing - Environmental, part, and maximum pre-acceptance operational limits; (e) Integrating equipment; (f) Parts R improvement program; (g) Defective or inadequate parts/specs; (h) Critical items; (i) Apportionment and Math Models - R Prediction; (j) Design Reviews; (k) Supplier and Subcontractor R Program; (l) R indoctrination and training; (m) Human Engineering; (n) Statistical methods; (o) Safety engineering; (p) Maintainability; (q) Failure data collection, analysis, and corrective action; and (r) Test plans.

MIL-STD-882, SYSTEM SAFETY PROGRAM, 1969.

Gives requirements and criteria necessary for establishing and implementing a system safety program. Also provides guidelines for the preparation of a System Safety Program Plan.

MIL-STD-891A, CONTRACTOR PARTS CONTROL AND STANDARDIZATION PROGRAM, 1972.

This standard establishes the criteria and guidelines for the preparation and implementation of a planned contractor parts control and standardization program. Includes (a) Reference Documents; (b) Definitions; (c) General Requirements; (d) Detail Requirements; (e) Equipment Performance; (f) Data and graphics designating parts selected for proposed and additional program preferred parts lists.

RADC-TR-69-458, NONELECTRONIC RELIABILITY NOTEBOOK, 1969.

Selects those useful reliability analysis methods that have been developed over the years and are applicable for the types of parts of concern, and collects them under one cover for the use of the designers employing these classes of parts. Seeks to present the methods in their most direct and useful form in a step-by-step instruction accompanied by appropriate examples. Contains sections concerning: (a) Part Failure Data - generic failure rate information for approximately 100 different parts, (b) Part Failure Rate - definitive breakdown of part types and their failure rates; and (c) Analytical tools - Applicable Statistical Methods, Prediction Methods, Demonstration Test Methods, and Reliability Specifications. Provides statistical tables to facilitate employment of the various methods described in the notebook.

RADC-TR-75-149, RELIABILITY, MAINTAINABILITY AND AVAILABILITY ANALYSIS TRADEOFF TOOL, 1975.

A computer program written in Honeywell Fortran for the Honeywell 645 Time-Sharing System, to model and calculate complex configuration/system reliability and maintainability values, a brief discussion of the reliability concepts utilized and examples of the program utilization/implementation are presented.

RADC-TR-76-32, GUIDELINES FOR APPLICATION OF WARRANTIES TO AIR FORCE ELECTRONIC SYSTEMS, 1976.

The basic types of warranty plans involving longterm contractor committment and incentives are reviewed. These include the Reliability Improvement Warranty (RIW), MTBF guarantee, and logistic-support-cost (LSC) committment. The guideline provides information on determining the applicability of these approaches and on developing an appropriate set of terms and conditions. Administrative procedures for developing and implementing a warranty are provided, together with evaluation procedures for monitoring warranty performance. A life cycle cost model is also presented to assist in evaluating warranty procurement in comparison with a totally organic maintenance approach.

RDH-376, RELIABILITY DESIGN HANDBOOK

The handbook provides guidelines for use by design engineers to assure the achievement of a reliable end product. From the standpoint of design, it is consistent with, and extends, basic concepts and reliability improvement techniques described in MIL-HDBK-217B. Specifically, the handbook provides design information factors, and parameters, and other engineering data affecting reliability. In addition, the handbook describes the approach to reliable design, includes theoretical and cost considerations and describes methods covering such considerations as part control, derating, environmental resistance, redundancy and design evaluation.

TM 38-750, THE ARMY MAINTENANCE MANAGEMENT SYSTEM (TAMMS), 1972.

Prescribes the equipment record procedures known as TAMMS, based on the concept of recording essential data concerning equipment operation and maintenance. Seeks to record the minimum of data, yet record all that is required for control, operation, and maintenance of equipment at each level of command. Establishes the minimum records and items of equipment on which the recording of operational and maintenance data is required at the organizational and national level. (Intermediate commanders may establish additional data collection to facilitate management of their operational and logistics responsibilities.) Includes instructions for the completion of forms and records, and for the control and management of equipment at organizational level. Includes procedures for processing and use of the forms and records by the organization. Covers the areas of (a) Operational Records; (b) Maintenance Records; (c) Historical Records, (d) Ammunition Records and Procedures, and (e) Calibration Records and Procedures. Includes data on Failure Codes (numerical and alphabetical).

Applies only to the organizational level.

TM 38-750-1, THE ARMY MAINTENANCE MANAGEMENT SYSTEM (TAMMS) FIELD COMMAND PROCEDURES, 1972.

Prescribes a procedural guide for the collection and processing of the data generated in accordance with TM 38-750 (full knowledge of the procedures in TM 38-750 is necessary to understand and properly utilize this manual), and utilization of maintenance and materiel readiness at field command level. Seeks to provide commanders and maintenance managers information necessary for (a) evaluating the effectiveness of maintenance operations; (b) assessing the performance of equipment; (c) determining the material readiness posture and condition of assigned materiel; (d) determining the status of equipment in terms on configuration control (MWO application); and (e) determining the adequacy of resources to accomplish the maintenance mission. Includes procedures for accounting man-hour and workload. Establishes procedures for a feedback of collected maintenance and material readiness data to assist major and intermediate effort. Covers the areas of (a) Maintenance Control; (b) Maintenance Data Collection and Processing; (c) Materiel Readiness; (d) Materiel Density Control; (e) Equipment Performance; (f) Maintenance Performance (including NORS/NORM feeder data); and (g) Configuration Control. Includes instructions for editing, card format, and keypunch (also MWO); and a processing guide for maintenance man-hour accounting.

ACQUISITION APPLICATIONS, U.S. Air Force/LGPS, 1976.

Acquisition Applications is a seminar conducted to provide information regarding Life Cycle Cost Procurement. This is accomplished by providing concepts for LCC policy and background, approaches and techniques, and also on two associated methods, Design To Cost (DTC) and Reliability Improvement Warranty (RIW). The seminar consists of 14 seminars entitled: (1) Introduction to Acquisition Applications; (2) LCC Policy and Background; (3) LCC Approaches and Techniques; (4) LCC Approaches and Techniques; (5) DTC Background and Concepts; (6) Implementing DTC; (7) DTC in Action; (8) RIW Background, Goals, and Airline Experience; (9) RIW Applications in DoD; (10) RIW Case Studies; (11) LCC Procurement; (12) LCC Procurement - Case Studies; (13) Putting it all Together - F-16 Case Study; and (14) Seminar Summary. The Seminar Guidebook also includes Supplements for LCC, DTC, and RIW; and General Acquisition Information.

ADVANTAGES AND LIMITATION OF ADVANCED MAINTAINABILITY CONCEPTS, Knapps, P.M., Proc. of 1969 Automat Support Systems Symp. for Advan. Maintainability, IEEE, St. Louis Soc., Nov. 3-5, 1969, Paper 5C, p 209-13.

Four aspects of advanced maintainability are discussed to highlight their advantages and limitations. These concepts include BITE, test connectors, ATE compatible avionics, and fault detection vs fault isolation test philosophies.

AIRCRAFT AVIONICS (DIGITAL AVIONICS STUDY), VOLUME IV, APPENDIX C, COST TRADEOFF ANALYSIS, Bright, Boris E., AD 916 533.

Current USAF avionics acquisition practices breed "black box" proliferation with all its attendant high costs, low reliability and heavy O&M burden. This is happening while digital technology threatens to inundate the service logistic channels. Enough technology is in hand to create prototype "digital avionics." Software turns out to be the single most deficient technical area. The board concludes that properly exercised avionics general systems engineering (GSE) can cause the much needed turn about in this avionics situation. The board has identified practices and facilities needed to asequately conduct avionics GSE (Volume I). Volume IV is a treatise on cost trade analysis. This volume indicates the importance of life costing (LCC) and the considerations that must be given to the "...ilities" if cost effective avionics are to become a reality.

ALLOCATION, ASSESSMENT AND DEMONSTRATION OF SYSTEM MTTR, Almy, G.H., R&M Conf., Anaheim, California, v 10, June 27-30, 1971, p 172-7.

APPLICATION OF THE MAINTENANCE FREE SYSTEMS APPROACH, Rivers, M.R., Tappi, v 54 n 6, June 1971, p 959-61.

Maintenance free systems are available, as evidenced by the household refrigerator, the wristwatch, some turbogenerators, and some of the new compressed air packages. Most of today's industrial systems fall far short of the maintenance free concept because of poor system design. Examples of poor system design are given and discussed. They include - roofs, pumps, instrumentation, heating and ventilating, self-monitoring, insulation and piping. Maintenance free system as a main requirement for the future.

APPLICATION OF HELICOPTER MOCKUPS TO MAINTAINABILITY AND OTHER RELATED ENGINEERING DISCIPLINES, Hawkins, Edward David, AD 786 500/9ST.

The purpose of the study is to present applications of helicopter mockups to the engineering disciplines involved in the design. The paper consists of a series of examples and suggestions, discussing how mockups can be used for (1) Integration and coordination between customer/contractor/vendor levels; (2) coordination between engineering design and support groups at the contractor level; (3) improved design and demonstration of human factors and maintainability related functions. Proper application of mockups results in a savings of time, materials, and money during the later states of development. The final outcome is a more cost effective project.

ART OF MAINTAINABILITY, Goldstein, S., Product Assurance Conf. and Tech Exhibit, Trans. Hempstead, N.Y., June 6-7, 1969, p 102-7.

Need for use of intuition to arrive at adequate design when maintainability considerations are included at early stage of design discussed: several examples are presented of result of applying intuition to real life situations in avionics; requirement problems and three resultant avenues of solution are described; maintainability design in mechanical systems is also discussed.

AUTOMATED TEST AND DIAGNOSTIC EQUIPMENT FOR USE IN THE MAINTENANCE AND REPAIR OF MECHANICAL EQUIPMENT, Hyatt, Lloyd W., AD 846 559L.

The report discusses the testing and evaluation of a computer aided diagnostic unit used to determine malfunctions in automotive engines.

A CASE STUDY OF REPAIR/DISCARD IMPLICATIONS IN ILS, Dorsey, Edward Bryant; Misner, Malvern Maynard; AD A003 791.

Integrated Logistics Support (ILS) is a relatively new concept involving many interrelated operations that are critical to the effectiveness of the final product. The thesis is designed to introduce students to the difficulties of implementing ILS in Navy acquisition projects. A case study is developed around the repair/discard decision that impacts heavily on life cycle costs. Background information is provided for students with limited experience in ILS.

CH-47A ASSESSMENT AND COMPARATIVE FLEET EVALUATION: EXECUTIVE SUMMARY REPORT, AD A002 057.

The purpose of the executive summary is to provide an overview and summarization of the CH-47A assessment. The parameters presented provide management perspective of the CH-47A fleet, in addition to comparative fleet evaluations. Various presentations of relibaility and maintainability related parameters give the present system posture of the CH-47A fleet. Model designation series assessment and comparative fleet evaluations are covered in this report. Quality and command program assessments and the command statistics and problem summary are the other reports which make up the total executive summary for the CH-47A.

A COMPUTER MODEL FOR ECONOMIC ANALYSIS OF ARMY AIRCRAFT RAM IMPROVEMENT PROPOSALS, Kassos, Tony, AD 778 551.

The report has been prepared for presentation to the Joint AMC/TRADOC RAM Seminar scheduled for 4th Quarter, FY 1974, at Fr. Lee, Virginia. AR 702-3 Army Material Reliability, Availability and Maintainability (RAM), 22 March 73 places increased emphasis on the cost impact of RAM efforts. This division was invited by the seminar sponsors to deliver a presentation of an economic analysis model developed here and to discuss how it could be applied to RAM cost studies. This report is in response to this request. A computer model is presented for preparing the cost tradeoff studies of RAM efforts required by AR 702-3. The model is specifically directed to RAM efforts involving Army aircraft. It determines the total life cycle cost impact of a RAM effort and pertinent RAM parameters. It is a modification of the economic analysis model mentioned above and is a preliminary effort to combine the methodologies of cost analysis and product assurance.

COST ANALYSIS -- WHAT IS IT, WHAT SHOULD IT BE, McGuire, Thomas E., AD 912 083L.

The technique of cost analysis was introduced to the military services by the Rand Corporation in 1948 as a consequence of the strategic bombing surveys. This management tool became more widely used during the period after the Korean War as the cost of military hardware began escalating. The increasing demand on the nation's resources for solutions to social problems requires efforts to optimize the military power purchased with limited funds. This study examines some of the techniques used in cost analysis and reviews the relative usefulness of each method. This study concludes that accurate cost estimates are available only in degrees as the government moves from early development to initial procurement.

COMPUTER SIMULATION OF LIFE CYCLE COST ELEMENTS, Booth, C.E., Jr.; Am Soc Quality Control-Annual Tech Conf, 23rd Trans., May 5-7, 1969, Los Angeles, Calif., p 731-40.

Life cycle costs of complex military avionics and electronic equipment.

COST EFFECTIVE APPROACH TO INTEGRATED LOGISTIC SUPPORT Duhan, S.; Myslicki, P.; 8th R&M Conf. (Annals of Assurance Sciences, v 8), July 7-9, 1969, p 470-5.

A single computer oriented system for Integrated Logistics Support, tied in with the system engineering process was developed by the Boeing Company, Vertol Division to reduce the costs resulting from operating separate systems for each of the military services.

COST EFFECTIVE TRADEOFFS BETWEEN MAINTENANCE PROCEDURES FOR GROUPS HAVING SEQUENTIALLY DEPLOYED SYSTEMS, Am Soc for Quality Control-10th Annual West Coast Reliability Symp., Los Angeles, Calif., Feb 21, 1969, p 1-19.

Model is presented which can evaluate the costs of alternative maintenance policies that provide a given group effectiveness. Groups are considered whose systems have been sequentially deployed into the field and require replacement/repair to sustain a given effectivity level. Group effectiveness is defined in the instantaneous sense, and is the ratio of the number of systems capable of performing as required upon demand to the total number of systems in the group at a given instant of time. Penalty or strategic loss costs, logistics costs and constant costs are determined; optimum maintenance policy is determined.

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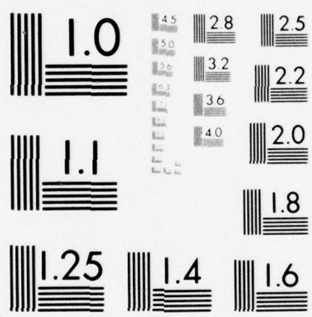

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COST ESTIMATING RELATIONSHIPS FOR FIELD AND DEPOT MAINTENANCE PARTS COSTS OF ARMY TURBINE POWERED HELICOPTERS: ARMY STOCK FUND PARTS: PEMA SECONDARY PARTS, Albright, D.L., AD B004 170L

This report presents two new AVSCOM cost estimating relationships (CERS) that estimate airframe and engine maintenance parts cost per flying hour for Army turbine powered helicopters. They are primarily intended for use in estimating operating cost for a peacetime environment. These new CERS are provided as alternatives, and not replacements, to those published previously by AVSCOM in May of 1972. One of the CERS estimates the cost of Army stock fund parts consumed in the field and depot; the other estimates the cost of replacing PEMA secondary parts lost due to attrition in the field and the depot. A technique is discussed regarding adjustments for improvements in reliability. The parts cost factor used to develop these CERS are also compared to the AVSCOM CERS documented previously, as well as to Navy and Air Force parts cost factors.

DESCRIPTION OF A COMPUTERIZED MODEL FOR SPECIFYING MAINTENANCE SYSTEM CONFIGURATION, Stettler, J.A.; Proc of 1969 Automat Support System Symp for Advan Maintainability, IEEE, St. Louis Sec., Nov 3-5, 1969, P 5D, p 21523.

A computerized model is described which provides a mathematical tool for systematic analysis of alternate implementation of a shipboard performance and maintenance monitor and reporting system. Alternate system configurations are traded off in terms of operating efficiency, time expended and cost. The unique feature of this model is that it treats maintenance function as an information flow network.

DESIGN FOR MAINTAINABILITY. AN INTRICATE SIMPLICITY, Heyligers, J., N74-16736/2.

Aircraft maintenance, when analyzed from an operator's point of view, will yield basic maintainability requirements which can be translated into general guidelines for design. The simple picture is greatly complicated when specific conclusions are to be drawn for all areas of airframe and system design and when, in the various phases of a project, the realization of maintainability is actually to be pursued and controlled. Source aspects of this process, which also involves endurance and reliability, are dealt with in more detail and illustrated by examples from the actual practice of aircraft design and operation.

DESIGN MAINTAINABILITY INTO EQUIPMENT, Goldstein, Siegfried; Electronic Design v 23 n Feb. 15, 1975, p 70-4.

Some basic guidelines for the design of maintainable equipment are given. Suggestions are given to: use quick disconnect latches, steep angle screws and any other type of retainer that reduces access time to internal components; break the circuitry up into small functional building blocks, and position test points to allow for branching; place the subsections that are most likely to fail closest to the repair openings; and give preference to simpler packaging to allow easy access to circuit boards, mechanical assemblies and test points.

DEVELOPMENT OF A RELIABILITY AND MAINTAINABILITY ANALYSIS TECHNIQUE FOR HELICOPTER RESEARCH AND DEVELOPMENT, Peake, James E., AD 772 955/1.

A program was conducted to develop analysis techniques that would facilitate the tasks of estimating the impact of predicted component reliability and maintainability (R&M) on an aircraft system in an Army operating environment and evaluating and ranking competing component concepts on the basis of their R&M characteristics. The effort included origination of algorithms that prepare R&M data for Army helicopter operations and maintenance (O&M) simulation, preparation of an O&M simulation model to investigate component impact in an Army environment, and preparation of a specialized life-cycle-costing approach for ranking competing component configurations on the basis of their relative cost impact (considering directly related component costs and changes in aircraft/system costs attributed to component R&M characteristics).

DEVELOPMENT OF MAINTAINABILITY TECHNOLOGY FOR SPACE VEHICLES, Prumkin, B.; Product Assur Conf & Tech Exhibit, Trans. Hempstead, N.Y., June 6-7, 1969, p 151-7.

Discussion of current in-house studies and investigations pursuing such aspects as the determination of optimum levels of maintenance, and design of equipment.

DEVELOPMENT PROGRAM FOR FIELD-REPAIRABLE EXPENDABLE MAIN ROTOR BLADES. PHASE I PRELIMINARY DESIGN, Grengley, M., AD 783 444.

The report presents the work done in evaluating the design concepts applicable to helicopter main rotor blades; assessing costs, repairability, maintainability, and survivability; and determining overall blade related costs, without technical compromise is chosen for further development. The application of maintainability and reliability criteria during the preliminary design phase has resulted in a significant

theoretical reduction in potential blade-related life cycle costs. These criteria were applied to all the field-repairable/expendable main rotor blade concepts examined, and all show a reduction in cost below that of the current blade. The selected concept has extruded aluminum spar and trailing edge spline, grass-fiber-reinforced-plastic skins, nylon paper honeycomb core, and built-up laminated metal root.

ECONOMICS OF INTRODUCING AUTOMATIC DIAGNOSTIC EQUIPMENT TO DIRECT AND GENERAL SUPPORT MAINTENANCE (ATE/ICEPM-DS/GS), Brachman, Raymond J.; Todaro, John B.; AD 847 835L.

This report represents an economic analysis of the impact of the application of automatic diagnostic equipment to combat-type and transport type vehicles. The principle function of the ATE/ICEPM is to automatically diagnose at the DS/GS levels, malfunctions in the fuel, electrical, cooling, oil and engine components for both types of vehicles with limited transmission testing of combat vehicles. It is concluded that the expected savings are sufficiently large to recommend the immediate implementation of ATE/ICEPM (QMR).

ECONOMICS OF INTRODUCING AUTOMATIC DIAGNOSTIC EQUIPMENT TO ORGANIZATIONAL MAINTENANCE (ATE/ICEPM-ORGL), Brachman, Raymond; AD 840 182L.

This report represents an economic analysis of the impact of the application of organizational automatic diagnostic equipment to combat-type and transport type vehicles. The principle function of the ATE/ICEPM (ORGL) is to automatically diagnose at the organizational level, malfunctions in the fuel, electrical, cooling, oil and engine components for both types of vehicles with limited transmission testing of combat vehicles. It is concluded that the expected savings are sufficiently large to recommend the immediate implementation of ATE/ICEPM (ORGL).

ENGINEERING DESIGN HANDBOOK MAINTAINABILITY GUIDE FOR DESIGN, AD 754 202.

The objective of this handbook, Maintainability Guide for Design, is to influence design so that the equipment can be (1) serviced efficiently and effectively if servicing is required, and repaired efficiently and effectively if it should fail, or (2) operable for the period of intended life without failing and without servicing, if possible. The designer who considers the technology of maintainability as one of the prime design considerations can play a vital part in the solution of the Maintenance Problem whereas the designer who fails to do this adds to the intensity of the problem. Part One describes the extent of the maintenance problem in

terms of the expenditure of money, men and material. Part Two presents maintainability objectives, principles, and procedures. Part Three describes the nature of the maintenance problem in terms of the conditions under which weapon systems must be operated and maintained.

AN EVALUATION OF MAINTAINABILITY REQUIREMENTS PRESENTLY BEING STATED IN GOVERNMENT CONTRACTS, Stratton, Willard F.; AD 739 154.

The paper summarizes the results obtained from a survey of maintainability oriented individuals. Contractors and government personnel were contacted to determine information about maintainability program plans and maintainability contract specifications. Specific information concerning the frequency and mode of different quantitative requirement specifications and general information concerning the opinions and recommendations of contacted personnel are presented and discussed. The paper concludes with recommendations for improving maintainability programs and quantitative specifications.

EVALUATION OF PROPOSED CRITERIA TO BE USED IN THE SELECTION OF CANDIDATES FOR RELIABILITY IMPROVEMENT WARRANTIES. Dunn, Payton E., Jr.; AD A006 335.

As DoD's percentage of the budget continues to decline. there is an increasing need to get more for the defense dollar. One way to achieve this objective is through the use of reliability improvement warranties (RIW). The RIW calls for a total repair contract based on a predetermined mean time between failure (MTBF). The contractor to whom the contract is let can realize increased profits by increasing the MTBF of the item. He does this by initiating "no cost" engineering change proposals which will increase time performance and reliability. The study was designed to survey the existing population of items covered by a RIW to determine what characteristics they had in common.

EXACT ANALYSIS OF THE METHOD-ONE MAINTAINABILITY DEMONSTRATION PLAN IN MIL-STD-471, Oksoy, Dolun; IEEE Trans. on Reliab. v R-21, n 4, Nov. 1972, p. 207-11.

The direct method in sequential analysis is used for an exact analysis of the Method-One maintainability demonstration plan in MIL-STD-471. Method-One is a nonparametric binomial sequential test and consists of three plans: A, B1, and B2.

EXECUTIVE SUMMARY REPORT ON CH-54A ASSESSMENT AND COMPARATIVE FLEET EVALUATIONS, AD 779 517.

The purpose of the executive summary is to supplement the management summary report. It is an overview and summarization of the material contained therein. The parameters presented provide management perspective of the CH-54A fleet, in addition to comparative fleet evaluations. Various presentations of RAM related parameters give the present system posture of the CH-54A fleet. MDS assessment and comparative fleet evaluations are covered in this report. Quality and command program assessments and the command statistics and problem summary are the other reports which make up the total executive summary for the CH-54A.

EXECUTIVE SUMMARY REPORT ON QUALITY AND COMMAND PROGRAM ASSESSMENTS, AD 779 518.

The purpose of the executive summary is to supplement the management summary report. The quality and command program assessment portion of this report is designed to provide an overall picture of quality on aircraft or components. The report assesses quality-related problems experienced in the field by the user as well as quality problems occuring at the Army plant, activities, and their impact on delivery schedules to the user. Quality and command program assessments are covered in this report. MDS assessment and comparative fleet evaluations, command statistics and problem summary, are covered in a companion report.

A GENERALIZED APPROACH FOR EVALUATING LOGISTICS STRATEGIES DURING ADVANCE PROCUREMENT PLANNING, Yatras, Dennis Andrew, AD A007 652.

This thesis presents a methodology for evaluating competitive logistics strategies early in the acquisition sequence. The author reviews the system requirements determination process and defines the role of advance procurement planning. Within this context, a system model is developed which provides visibility of the cost and effectiveness impacts of alternative combinations of reliability, maintainability, and supportability parameters.

GENERALIZED PROCEDURE FOR EVALUATION OF MAINTENANCE AIDS, Ford, W.F., Foster, J.W.; Reliability and Maintainability Conf., Anaheim, California; v 10, June 27-30, 1971; p 291-300

GOVERNMENT DEPOT MAINTENANCE WARRANTIES, Hunt, Don; Genet, Russel; Crossier, Theodore; AD 922 375L.

This paper introduces the concept of government depot maintenance warranties for consideration as a valid government depot maintenance contracting technique. The paper examines the advantages and disadvantages to be expected from such a concept and briefly describes what a depot maintenance improvement warranty might consist of and how it might work.

GUIDELINES FOR APPLICATION OF WARRANTIES TO AIR FORCE ELECTRONIC SYSTEMS, Balaban, Harold S.; Retterer, Bernard L.; AD 023 956.

The guidelines developed in this study include criteria for selection of candidate systems for warranty application, a computer based cost estimating model which permits comparative evaluation of warranty versus organic maintenance costs, warranty evaluation methods, sample warranty provisions, and warranty administration procedures. A case study of the AN/ARN-118 TACAN procurement is presented to illustrate the application of these concepts.

HELICOPTER TRANSMISSION MODULARIZATION AND MAINTAINABILITY ANALYSIS, Kish, Jules G.; Menkes, Paul; Cormier, Kenneth R.; AD 775 834/5.

The objective of the transmission modularization analysis was to develop a methodology to evaluate helicopter transmission modularization and to demonstrate the feasibility, methods, design and criteria, and cost effectiveness of modularization. A U.S. Army CH-54B helicopter was selected for the analysis and designs were completed for transmissions with seven, six, four and three modules. A mathematical model was derived that calculated the cost and performance characteristics of a helicopter with a modularized transmission. A computer program was written to implement the mathematical model.

IMPACT ON ENGINE MAINTAINABILITY OF GASEOUS RADIOACTIVE PENETRANT INSPECTIONS, Eddy, W.C., Jr., Proc. Ninth R&M Conf., Detroit, Michigan v 9, July 20-22, 1970, paper 700598, p 205-10.

Recent developments of radioactive gas penetrants have shown a capability for measuring microscopic defects as are present in early low cycle fatigue. Reliable detection of these defects points the way to aircraft engine maintenance predicated on "condition" removal rather than time. The paper will deal with work now in progress using the new penetrant system on aircraft materials having defects typical of early low cycle fatigue

AN INVESTIGATION INTO THE USE OF COMPUTER MODELS DURING CONCEPTUAL PHASE LOGISTICS PLANNING, Labelle, Joseph P.; Turner, Robert F.; AD 750 916.

Integrated logistics support (ILS) policy and guidance within the DoD and the Air Force refer to a relatively sophisticated process of quantitative analysis as being essential to logistics support planning during all phases of the system acquisition life cycle. The feasibility and practicality of using computer programmed simulation and analytical models during conceptual phase ILS planning are examined with emphasis on Air Force Electronic system acquisition programs. Five existing logistics models are evaluated for compatibility with the quantitative requirements and availability of source data within the conceptual phase ILS planning environment. Conclusions and suggested prerequisites for implementation are presented.

LIFE CYCLE COST ANALYSIS GUIDE, Menker, Lavern J., Nov. 1975, APAFB, Ohio.

This document provides guidance on the use of life cycle cost analysis covering a broad spectrum of acquistion program issues. Changes have been made in this publication to reflect comments and suggestions on the June 1975 edition. This guide should help program managers determine, describe, and manage life cycle cost analyses needed for program decisions. It should also help cost, operations research, and other analysts organize and initiate life cycle cost analysis efforts.

LIFE CYCLE COST/SYSTEM EFFECTIVENESS EVALUATION & CRITERIA, Walker, G.A., AD 916 001.

This document contains results of an independent research and development task on life cycle cost performed by Boeing Aerospace Company. This seven month study is Phase I of a planned continued effort and includes discussion on life cycle cost current state-of-the-art, a planned approach and recommendations on where emphasis should be placed to effectively perform cost analysis studies on new systems. Included is a bibliography of 160 documents relevant to life cycle cost, and an evaluation of 14 computer programs which provided the data base from which cost consideration elements and new criteria were developed.

LIFE CYCLE COSTING APPLIED IN EVALUATING ALTERNATIVE SHORT TAKE-OFF AND LANDING (STOL) AIRCRAFT AND TRACKED AIR CUSHION VEHICLES (TACV) AS MODEL OF TRANSPORTATION, Langworst, C.H., R&M Conf., Anaheim, California, v 10 June 27-30, 1971, p 231-35.

A LOGISTICS LIFE CYCLE SUPPORT COST MODEL, Baron, David A.; Mortenson, Robert E., Jr.; AD 863 842.

Life cycle costing, integrated logistic support, and maintainability and reliability provide the concepts necessary to construct a mathematical model for predicting the effect changes in maintainability and reliability will have on the life cycle costs of the logistics elements affected. The thesis develops such a model and then examines the effects changes in maintainability and reliability have on logistics life cycle cost can be described as a linear function while changes in reliability can be described as a negative exponential function.

LOGISTICS SUPPORT LIFE CYCLE MODELING, Sterkel, Terrance E., AD A009 290.

Using existing Army conceptual life cycle management models a basic logistics support life cycle model was made. Changes dictated by material acquisition policy, and contemporary logistics support concepts were included. An interactive graphics system was utilized to generate and store the finished logistics support life cycle model. The model is oriented toward application by the practicing logistics/maintainability engineer. As such, emphasis is on compatibility with existing system models.

MAINTAINABILITY ANALYSIS OF MAJOR HELICOPTER COMPONENTS, Cook, Thomas N.; Young, Robert L.; Starses, Frank E.; AD 769 941/6.

The report examines the factors responsible for the high man-hour cost of maintaining current-inventory Army helicopters. Major components of six helicopter models were analyzed to identify the significant man-hour consumers on each aircraft. Causes for maintenance were established in terms of failure modes, maintenance frequency, and average repair time. Major component replacement tasks were structured in terms of specific time elements, and important factors affecting maintenance task performance were established. The report documents the results of three study tasks: using data derived from the analysis, a checklist has been developed for use in maintainability analyses of future helicopter designs.

MAINTAINABILITY ENGINEERING DESIGN NOREBOOK, REVISION II, AND COST OF MAINTAINABILITY, AD A009 043, 044, 045.

This notebook brings together currently available knowledge of maintainability engineering and treats such knowledge from a practical rather than theoretical viewpoint. The notebook provides both quantitative and qualitative information and techniques which can serve as guidelines for those personnel who are directly responsible for establishing maintainability requirements and maintainability design, and for the acceptance of the maintainability of Air Force ground electronic systems and equipments.

Although the notebook is directed at ground electronic systems, the majority of the material is applicable to a much broader class of hardware.

Specifically, the notebook includes a description of the time phasing of the maintainability program tasks, a breakdown of maintainability into its roots, and detailed description, guidelines and methodology, procedures, and an example of each maintainability task, as applicable.

Since maintainability covers a wide range of disciplines ranging through electronic and mechanical design, instrumentation requirements, logistic support, personnel requirements, and statistics, it is not anticipated that any single group will find all of its responsibilities completely described in this notebook. It should, however, contribute significantly to improved maintainability programs and subsequent improved system/equipment maintainability.

It is intended that the notebook will be updated and revision issued as necesary to enhance its applicability and maintain its currency with advances in the maintainability discipline.

MAINTAINABILITY, A TOTAL SYSTEM VARIABLE, Sanderson, J.V.; Suslowitz, R.; Product Assurance Conf & Tech Exhibit-Trans. Hempstead, N.Y., June 7-8, 1968, p 51-60.

Approach is presented which views maintainability for its impact on acquisition management (people), design (hardware), and operational effectiveness (people/hardware). Tools and techniques are presented within a total system framework and within the context of DoD and Navy requirements. These tools and techniques encompass data processing, data retrieval, and design criteria.

MAINTAINABILITY CONCEPTS USED IN THE DESIGN AND OPERATION OF DOUGLAS COMMERCIAL JET AIRCRAFT, Bandy, J.M., SAE Prepr Pap n 730881 for Meet Oct 16-18, 1973, 4p.

This paper explains the maintenance philosophy at Douglas Aircraft and gives examples relating to the DC-8, DC-9, and DC-10. The three methods of maintenance control -- Hard Time, On Condition, and Condition Monitoring -- are described, and statistics of Delta Air Lines Maintenance provided to illustrate their effectiveness.

MAINTAINABILITY DEMONSTRATION PROCEDURE AND DATA, Cunningham, C.E., Product Assurance Conf & Tech Exhibit-Trans., Hempstead, N.Y., June 7-8, 1968, p 85-95.

Seventeen maintainability demonstrations have been performed over the last six years. Each demonstration was a separate effort performed to determine the degree to which the contract end item of ground electronic equipment satisfied the maintainability requirements specified in the contract. Each subsystem tested was different, but most of the equipment in each was electronic. For each demonstration, a sample of malfunctions was established statistically to represent the lifetime population of corrective maintenance tasks expected for the given equipment. Methods for duplicating or simulating each malfunction were determined and the malfunctions were inserted, one at a time, into the installed equipment under as near to operational conditions as could be achieved.

MAINTAINABILITY/RELIABILITY IMPACT ON SYSTEM SUPPORT COST, Johnson, Walter L.; Reel, Rodney, E.; AD 916 434L.

This technical report addresses life cycle costs for fighter type aircraft, with emphasis on analysis performed during the early design phase. The engineer is provided a discussion of the factors and guidelines for estimating major elements of the life cycle costs for new or existing weapon systems using field experience data and cost planning factors from AFM 173-10. It does not include a computer model. Charts and curves are included which show how reliability and maintenance impact support costs during a program's operational phase. Quantifiable support cost savings have been calculated on the F-4, F-111 and A-7D aircraft to demonstrate the analytical approach and rationale used in performing the analysis.

MAINTAINABILITY, THE MEASURE OF AVAILABILITY, Wright, T.O., Eigth R&M Conference (Annals of Assur Sciences, v8) July 7-9, 1969, p 466-9.

A method of defining availability in terms of maintenance demand rate and mean downtime is presented. This involves combining distribution functions for secondary failures, wearout failures, handling damage, human error, performance deterioration, nonoperational defects, environmental effects, test equipment errors, and procedural errors with the primary failure rate calculations so that a mean time between maintenance actions can be determined.

MAINTENANCE REPLACEMENT SEQUENCE SELECTION, Nusbaum, M.R.; R&M Conf., Anaheim California, v 10, June 27-30, 1971, p287-90.

ON CONDITION MAINTENANCE PROGRAMS, Ahlbord, K.; Crabbee, S.; IEEE Proc Annu Symp Rel., Los Angeles, Calif., v 3 n 1, Feb 3-5, 1970, p 300-7.

The program depends primarily on statistical and engineering analyses and performance monitoring rather than on scheduled overhauls to determine operating limits.

OPTIMIZATION OF THE TIME BETWEEN AIRCRAFT OVERHAULS BY MINIMIZING MAINTENANCE COST, Smith, Shirley J.; Gaffney, Florence A.; Schulze, Billy R.; Fox, D. Frank; Stone, Blaine T., AD A006 505.

The purpose of the study was to investigate the feasibility of determining when an aircraft should be overhauled in order to minimize the life time maintenance cost of the aircraft. It was assumed that the cost of field maintenance increases as the aircraft's flight hours increase. Also, it was assumed that following an overhaul the cost rate drops significantly, then increases again until an overhaul. The total life time maintenance cost is the sum of all field maintenance costs and all overhaul costs. Then, the optimum time between overhauls was found as that time for which the life time maintenance cost is a minimum.

OVERHAUL POLICIES FOR MECHANICAL EQUIPMENT, Hastings, Najk; Thomas, D.W.; Inst. Mech. Eng. Proc. (Part 1), Gen. Proc. v 185 n 40, 1970-71, p 565-9.

Repair costs for mechanical equipment tend to increase with age. A mathematical expression relating mean repair cost to age is developed.

OVERVIEW OF U.S. ARMY HELICOPTERS STRUCTURES RELIABILITY AND MAINTAINABILITY, House, Thomas L., AGARD Rep. n 613, 1974, for Meet. Milan, Italy, April 2-6, 1973, 14pp.

Approximately 25% of all U.S. Army helicopter failures and field maintenance man-hours are related to structures. Externally induced damage is the primary cause of many failures, and it is the essential reliability and maintainability (R&M) consideration in the selection of rotor blade and transparency designs. With the exception of rotor blades, most structural failures are normally considered as maintenance downtime sensitive as opposed to a cost problem. Greatly improved design and test documents coupled with "lessons learned" appear to be the most responsive approach to gaining significant structures R&M improvements. Helicopters vibration reduction can produce a major reduction in secondary structural failures and maintenance rates.

A PARAMETRIC LIFE CYCLE COST MODEL FOR ARMY HELICOPTERS, Stanard, G. Norman; Martinez, Stephen M.; Malone, Mark J.; AD 919 317L.

This report presents a parametric life cycle cost model for Army helicopters, a computerized cost estimating tool. The model estimates the total life cycle cost of a new Army helicopter, including research and development, investment (recurring and nonrecurring), and operating cost. Whenever possible the model uses a parametric approach to estimate each segment of cost. For those segments of cost for which reliable historical data is not available, the model uses an estimate based on industrial engineering or experienced judgment. Appendices to the report include synopses of the reports describing the cost estimating relationships used in the model, the format of the input data to the model, the complete Fortran IV computer program listing, and the output from a sample program.

POTENTIAL OF PROJECT PRIME FOR PROVIDING HISTORICAL COST DATA REQUIRED IN INTEGRATED LOGISTIC SUPPORT PLANNING, Canon, Truman L.; Bredenkamp, Barton C.; AD 863 841.

The purpose of the thesis is to make a limited evaluation of the historical cost data collected by the prime (priority management efforts) system for use in making the cost estimates needed for planning integrated logistic support. Prime cost data associated with the base level maintenance function will be used in making this evaluation. This function was chosen because it is a major cost area in support of Air Force operations. Similar methodology could be applied for analysis of other support areas.

PRACTICAL LIFE CYCLE COST/COST OF OWNERSHIP TYPE PROCUREMENT VIA LONG TERM/MULTI YEAR 'FAILURE FREE WARRANTY' (FFW) SHOWING TRIAL PROCUREMENT RESULTS, Harty, J.C., R&M Conf. Anaheim, Calif., v 10 June 27-30, 1971, p 241-51.

PRACTICAL METHOD OF MAINTAINABILITY ALLOCATION, Chipchak, J.S., IEEE Trans. Aerosp. Electron Syst. v AES-7 n4 July 1971, p 585-9

A practical method of allocating the system maintainability (M) requirement to lower functional equipment levels is described. The use of this method minimizes trial and error in establishing values for each equipment item and the amount of tradeoffs required in apportionment relative to equipment complexity and M design characteristics.

PREDICTING MAINTENANCE TIME DISTRIBUTION OF COMPLEX SYSTEM. MONTE CARLO SOLUTION, Downs, W.R.; Am Soc for Quality Control-Tenth Annual West Coast Reliability Symp., Los Angeles, Calif. Feb 21, 1969, p 37-47.

Simulation program is discussed which was specifically developed to support maintainability analyses and design evaluation. Program is equally useful in predicting maintenance man-hours, elapsed time, or probability of meeting a maintenance schedule. Data requirements are limited to only four normally understood parameters - failure rate, operating time, and median and maximum repair times. Program computational process is described in sufficient detail that the experienced analyst should have no trouble adapting the program to his particular computer.

PREMATURE PERFORMANCE OF SCHEDULE MAINTENANCE, Barnes, K.G., R&M Conf., Anaheim, Calif., v 10 June 27-30, 1971, p 318-27.

RELIABILITY AND MAINTAINABILITY ANALYSIS OF A TWO-YEAR MANNED SPACECRAFT MISSION, Jennings, H.A.; J. Spacecraft & Rockets v 6 n 3 March 1969, p 327-9.

A mission simulation model was developed to simulate the unscheduled maintenance requirements of the space station. Unscheduled failures were assumed to occur randomly within an assumed exponential distribution about the total system mean time between failure. The mean expected spares usage varied from 95 lbs for 90 days to 700 lbs for 730 days. The expected impact of the unscheduled maintenance on the mission and crew operations indicates that on 88% of the days there will be no unscheduled maintenance required and on 98% of the days, no more than five hours will be required.

RELIABILITY ENGINEERING HANDBOOK, June 1, 1964, NAVAIR-00-65-502/NAVORD-OD-41146.

This handbook is primarily intended to fill the need for a manual of reliability methods suitable for use by project management and engineering personnel responsible for acquisition of reliable naval equipment and systems. Procedures are outlined and illustrated by practical examples for planning, analysis, test and evaluation, monitoring, and control of reliability throughout the system life cycle, with emphasis on the conceptual and early design phases of system development. While examples used to illustrate the procedures are drawn primarily from naval ordnance and aircraft systems, the procedures in themselves are generally applicable to any type of equipment or system for which a firm reliability requirement has been established.

RELIABILITY GUIDES, June 30, 1970, NAVORD OD-44622 (4 Volumes).

Volume 1 - Reliability Decision and Control presents guidelines for management and control of reliability in naval ordnance equipment and system acquisition programs. Procedures are intended primarily for use by project managers and equipment project engineers responsible for management and technical direction of concept formulation, design, development, production, and product improvement phases of the system life cycle, to assure delivery of reliable NAVORD systems and equipment to the operational fleet. Procedures are readily adaptable for use by contractors and subcontractors in the management and control of reliability in their respective areas of contract responsibility.

Volume 2 - Reliability Test and Evaluation outlines procedures for planning and conducting integrated reliability test programs for naval ordnance equipment and systems. Reliability rest considerations presented in this volume are in accordance with Volume 1 of the Reliability Guide series. Procedures are furnished for selection and design of specific types of tests to best satisfy reliability data requirements for decision and control at key decision points in the system life cycle. Procedures are also outlined for contractual specification of test requirements, acceptance criteria, and data requirements to establish the lefal basis both for Navy control of the test program and for accept/reject decision on the basis of test results.

Volume 4 - Reliability Data Analysis & Interpretation outlines procedures for the analysis and interpretation of data produced by test programs and fleet operational experience. Procedures are included for reliability modeling, data analysis, system reliability measurement, mission dependability evaluation, and problem definition. The volume is written as a complementary guide to Volume 2 of the series for use both in planning the test program to produce the required data and in analyzing results of individual tests in the program.

RELIABILITY OF AIRBORNE ELECTRONIC EQUIPMENT AND ITS EFFECT ON LOGISTICS REQUIREMENTS, Allen, John L.; Sloan, Harold J.; AD 806 827.

Reliability of airborne electronic equipment is studied in detail. Discussed are (1) the need for reliability in airborne electronic equipment, (2) methods used to obtain reliability of airborne electronic equipment, (3) the effects of reliability of airborne electronic equipment upon logistics requirements, and (4) future design of airborne electronic equipments, the anticipated reliability of future equipments, and the effects of future design and reliability upon logistics requirements. This thesis presents field failure data on one item of airborne electronic equipment, the AN/ARC-90 ultra high frequency radio set, currently in use only in the C-141A. The thesis draws conclusions relating to the varied methods by which mean time between failure is computed for airborne electronic equipment and the present method employed throughout Air Force logistics command by which demands for initial spares provisioning are predicted.

STATISTICAL APPROACH TO MAINTAINABILITY ALLOCATION, Perry, O.T., R&M Conf., Anaheim, Calif., v 10 June 27-30, 1971, p 164-7.

STATISTICAL MAINTAINABILITY DEMONSTRATION PLAN, Lavery, J.V., Jr.; R&M Conf., Anaheim, Calif., v 10 June 27-30, 1971, p 168-71.

STATUS OF MAINTAINABILITY MODELS: A CRITICAL VIEW, Smith, Russell L.; Westland, Ronald A.; AD 727 014.

Significant milestones in the development of maintainability assessment techniques are summarized. Maintainability models are validity, and use of human engineering data. The capability of each model to be employed during various points in the system development cycle is evaluated with special consideration given to availability of model input data. Examples of potential model approaches are included.

THE STATUS OF MAINTAINABILITY MODELS: A CRITICAL REVIEW, Smith, Russell L.; Westland, Ronald A.; Crawford, Billy M.; AD 751 343.

Significant milestones in the development of maintainability assessment techniques are summarized. Maintainability models are critically reviewed in terms of general utility, ease of application, validity, and use of human engineering data. The capability of each model to to employed during various points in the system development cycle is evaluated with special consideration given to availability of model input data. Examples of potential model approaches are included. Survey results show continuing progress toward the potential development of efficient maintainability modeling techniques.

However, increased effort is required to ensure the development of effective systems and to reduce maintenance costs. Emphasis is given to requirements for additional effort in (1) maintainability modeling early in the design process, (2) model validation, and (3) development of timely, valid input data.

SUBSYSTEM MAINTAINABILITY DEMONSTRATION, Lambert, S.G., Product Assurance Conf & Tech Exhibit, Trans., Hempstead, N.Y., June 6-7 1969, p 108-18.

Description of maintainability demonstration carried out on Government Furnished Equipment (GFE). Avionic subsystems of P-3C weapon system to determine whether or not subsystems had been designed to meet maintainability requirements and also to ascertain time required to make design changes prior to production; after discussing test results major functions performed are examined and Demonstration Report contents are presented: discussion of problems encountered and results obtained are included.

A SUMMARY AND ANALYSIS OF SELECTED LIFE CYCLE COSTING TECHNIQUES AND MODELS, Dover, Lawrence E.; Oswald, Billie E. Jr; AD 787 183.

Operational costs continue to recur throughout the life of a weapon system and normally represents the majority of life cycle costs. Presented are an "Annotated Bibliography of Selected Life Cycle Costing Literature" and a "Taxonomy of Selected Life Cycle Cost Models." The annotated bibliography is sectionalized into six areas; directives and guides; general philosophy and methodology reliability and maintainability; cost-effectiveness; cost models; and case studies and technical reports. The taxonomy discusses six types of life cycle cost models including accounting, cost estimating relationship, simulation, failure-free warranty, reliability, and economic analysis models. One conclusion is that awareness of life cycle costing concepts results in better planning and decision making.

SYSTEM IMPROVEMENT THROUGH MAINTAINABILITY DEMONSTRATION, Leuba, H.R.; Proc. Ninth R&M Conf., Detroit, Mich., v 9 July 20-22, 1970 Paper 700592 p 174-4.

Maintainability demonstration should be based on the whole operational setting. By so doing, and by establishing, beforehand, agreements between the contractor and the customer concerning parameter values and individual responsibilities, maintainability demonstration can be much more effective at influence system performance. Certain design/use tradeoffs become apparent, and both contractor and customer can see the system performance costs of their theretofore implicit assumptions. This contention is illustrated with a maintainability.

SYSTEMS MAINTAINABILITY MODELING, Regulinski, T.L., IEEE Proc. Annual Symp. Reli., Los Angeles, Calif., v 3 n 1 Feb. 3-5, 1970 p 449-57.

Stochastic modeling of the system parameter maintainability.

T63-A-5A ENGINE MAINTAINABILITY AND RELIABILITY, Piper, G.C., AD 750 645.

The report presents the results of mission and systems reliability investigations of in-service helicopter turbine enginer.

TECHNIQUE FOR DETERMINING THE NUMBER OF SPARES WITH A PRE-CHOSEN PROBABILITY LEVEL, Lynch, H.E.; Morris, R.S.; McNichols, R.J.; Shreve, D.R.; R&M Conf., Anaheim, Calif., v 10 June 27-30, 1971, p 287-90.

TOOLS OF MAINTENANCE, Higgins, Lindley R., Constr. Methods Equip, v 56 n 11 Nov. 1974, p 56-62.

The paper reviews the basics of maintenance shop tool selection, use and safety. Hammers, wrenches, pliers, saws, files and wheel pullers get thorough coverage. One section looks at the parameters of portable power tool usage. The latest techniques of tachometer operation are discussed.

USE OF A COMPUTER FOR PREDICTIONS OF MTTR OR EQUIPMENTS SUPPORTED BY AUTOMATIC TEST EQUIPMENT, Hilton, R.E., Jr.; R&M Conf., Anaheim, Calif., v 10 June 27-30, 1971, p 329-37.

USE OF COMPUTERIZED SUPPORT MODELING IN LOGISTICS SUPPORT ANALYSIS, Colon, W.M.; Calfapietra, V.G.; AD 783 487.

During recent years there has been a growing concern within the DoD for the consequences of ignoring predicted logistics costs for any given system while it is still in design. In order to deal with the problems of ownership, as well as acquisition of a system, one must be able to bridge the gap between the inherent characteristics of the design and environment in which the system will be operated and maintained. A valuable technique for identifying and evaluating the most cost effective options for management decision in this area is the performance of logistic support analysis (LSA) utilizing computerized support modeling. A demonstration of how computerized support modeling (GEMM) can be applied in this manner, is presented by considering the design and development of an electronics system for Army use. Two examples are provided in order to illustrate typical LSA's during both the advanced development and engineering development phases.

USE OF WARRANTIES FOR DEFENSE AVIONICS PROCUREMENT,
Balaban, Harold S.; Retterer, Bernard L., AD

The objective of this study was to investigate the potential benefit of using warranty agreements as part of military avionics procurements. The approach taken was to interview airline and military activities and their suppliers who in the past have made use of warranties. The survey was accomplished and included six airlines, six vendors, and seven military agencies. In addition to these interviews, a literature search was performed relative to past studied warranty usage. A life-cycle cost model was formulated which permits cost comparisons to be made between warranty and no-warranty procurements. The model permits the computation of the optimum warranty time period and break-even or indifference cost to identify the minimum added cost which may be spent on warranty coverage. A number of conclusions and recommendations stemming from the study are made concerning the application and administration of warranties for avionic systems. Also a Phase II program was outlined defining a program to further develop alternative warranty plans, analysis procedures and a validation program.

APPENDIX C

SAMPLE OPERATING PROCEDURES

APPENDIX C-1

STRESS ANALYSIS RELIABILITY PREDICTION PROCEDURE

APPROACH

Stress analysis worksheets aid in the reliability analysis of helicopter subsystems and components. As a reliability prediction technique, it provides the discipline required to analyze an assembly--component-by-component. Actual stress is compared with rated strength for each component and the base failure rate is adjusted according to the following formula.

$$\lambda_p = \lambda_b \pi_E \pi_{S2} + \Sigma_E$$

PROCEDURE

The stress worksheet shown in Figure C1-1 facilitates computation of derated part failure rates. Figure C1-1 also defines the symbols listed in the above equation. The part failure rates (λ_p) are summed to determine the assembly's total failure rate.

The worksheet provides for the following:

a) Identification of the assembly/subassembly.

b) Identification of each component/part.

c) Rating of each component/part. Rating is related to particular performance parameters appropriate for the component. Shaft horse power, flow rate, and pressure limit are ratings specified by component manufacturers. Rated performance is usually qualified at a reference temperature, humidity level, etc. Rating of parts and materials are usually specified as yield strength endurance limit, corrosion resistance, etc.

d) Load, thermal, vibration, level, and shock induced stress applied to each component. The applied stress should be converted into the same units as the rated strength. Only parameters that significantly affect reliability should be listed in the table. The ratio of rated strength to stress (stress ratio) is more commonly referred to as a factor of safety (F.S.) by designers.

STRESS ANALYSIS WORKSHEET SYSTEM: ______________________

Equipment		Assembly		Sub-assembly		
Name	Ref.Desig. / Dwg.	Name	Ref.Desig. / Dwg.	Name	Ref.Desig. / Dwg.	Sheet ___ of ___ / Date ___

Part / Component							Application Parameters										
Part Number	Reference Design	Ratings	Applied Stress (Pri/Sec)	Stress Ratio Pri/Sec	Comp. Temp.	Base Failure Rate λ_b	Environment Prod π_E	Environment Add Σ_E	Sec Stress π_{S_2}								Application Failure Rate λ_p

Figure CI-1
STRESS ANALYSIS WORKSHEET

e) The base failure rate, λ_b--at a specific rated load and thermal stress. The base failure rate is derived from large scale part test programs or carefully screened field data collection programs which have been sponsored by the military. Their objective is to define numerical relationships between stress/temperature levels and failure occurrence. The part failure rates derived from these programs are ordinarily kept free of biases introduced by particular equipment types and reflect only the basic part capability.

f) The application factors--including quality/environmental factors π_E and Σ_E and secondary stresses, S_z--required by the application of each component part. These factors are scaling parameters relating stress ratios to failure rates. The application factors may be derived using semi-empirical techniques or derived from testing program.

g) The application failure rate, λ_p--as determined by the base failure rate and application factors--for each component part.

APPENDIX C-2

FAULT TREE ANALYSIS PROCEDURE

PROCEDURE

The objectives of product fault tree analysis are:

- to assess the magnitude of potential failures, particularly those effecting safety at an early stage of product development, and
- to identify, rank, and catalog all possible failure modes and hazardous conditions so that effective corrective measures can be formulated and instituted prior to product use.

As discussed in Section 4.3.3.1, fault tree analysis is a methodology adopted and used to accomplish these objectives. The analysis starts with a specific failure condition (e.g., loss of power), and proceeds downward to define possible system and equipment faults, conditions, and user actions whose occurrence singly or in combination can cause this event. Logic diagrams are used to portray these basic faults, conditions, and events.

The fault tree analysis procedure involves five (5) steps as follows:

Step 1: Fault Tree Diagraming.

Step 2: Collecting Basic Fault Data.

Step 3: Computing Probability Numerics.

Step 4: Determining Criticalities.

Step 5: Formulating Corrective Action Recommendations.

Following is a simplified example of the FTA technique. This example is based on a safety analysis* performed on the OH-58 helicopter. Loss of hydraulic power in the event that potential faults and conditions which can lead to this event are identified.

* AVSCOM Reliability and Maintainability Technical Report 74-1. Identification of Safety-Critical Components and Characteristics of the OH-58A Helicopter.

Figure C2-1 presents a fault tree diagram that was constructed for loss of hydraulic power. Note that the figure is given to illustrate application of the technique; it is not intended to fully define the hydraulic reliability problem as it can exist with helicopters in their use environment. Actual diagrams for specific helicopters must be developed through a detailed review of individual design and application characteristics.

The fault tree indicates that loss of hydraulic power can be caused by:

(a) a hydraulic pump failure,

(b) a hydraulic by-pass solenoid failure,

(c) a line or fitting failure,

(d) a servo actuator failure,

(e) a filter system failure,

(f) a hydraulic relief valve failure.

The fault tree further indicates that two conditions are necessary to cause a filter system failure. The "and" gate symbol logically shows that both a clogged filter and a by-pass switch failure must occur in order to cause a fulter system failure.

Figure B3-2 presents a fault matrix prepared for this failure condition. Data and information tabulated in the matrix were developed using the methods and techniques described in Section 4.3.3.1 of this document. Based on the fault probabilities, $P(X_i)$ listed in Figure C2-2, and the fault tree logic diagram of Figure B3-1, a probability of 2.8×10^{-5} was computed for loss of hydraulic power (for a 2 hr. mission time period). Seven basic faults are identified in the matrix. Five of these are considered critical. Corrective measures can be established for the critical faults.

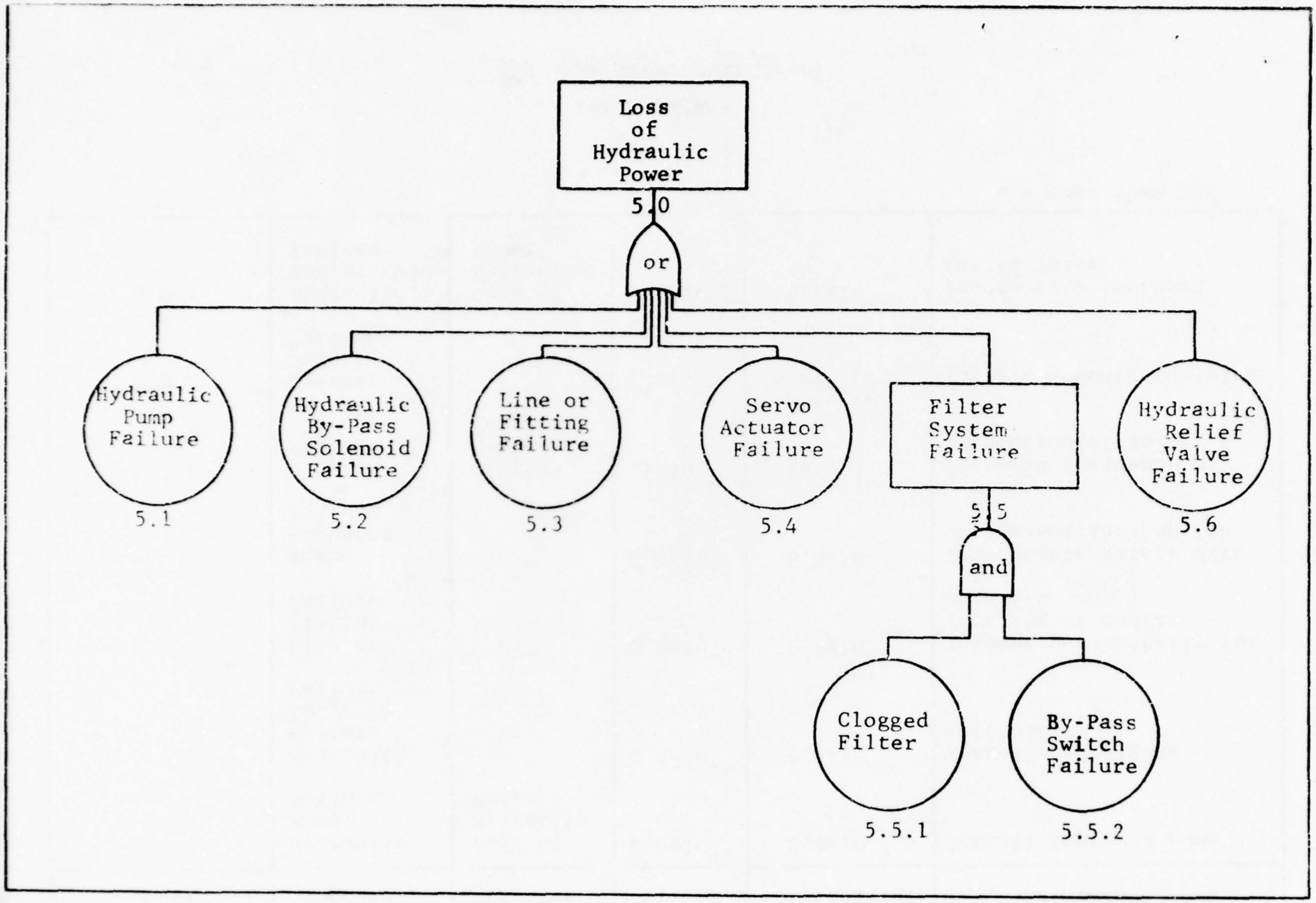


Figure C2-1

FAULT TREE DIAGRAM

Identification Number	Basic Fault	Failure Effect	P(x's)	Criticality	Corrective Action Recommendations
5.1	Hydraulic Pump Failure	Loss of Hydraulic Power	$0.8x10^{-5}$	$0.8x10^{-5}$	Install improved pump
5.2	Hydraulic By-Pass Solenoid Failure	"	$0.2x10^{-5}$	$0.2x10^{-5}$	Install redesigned solenoid
5.3	Line or Fitting Failure	"	$0.8x10^{-5}$	$0.8x10^{-5}$	Inspect periodically for fretting or contact abrasion
5.4	Servo Actuator Failure	"	$0.8x10^{-5}$	$0.8x10^{-5}$	Incorporate safety wire or jam-nut locking tab
5.5.1	Clogged Filter	Filter System Failure	$<1x10^{-5}$	$1x10^{-10}$	Increase frequency of inspection/cleaning
5.5.2	By-Pass Switch Failure	"	$<1x10^{-5}$	$1x10^{-10}$	Install redesigned switch
5.6	Hydraulic Relief Valve Failure	Loss of Hydraulic Power	$0.2x10^{-5}$	$0.2x10^{-5}$	Incorporate improved relief valve

$<$ = less than

Figure C2-2

FAULT MATRIX

(Derived from Fault Tree)

These measures could involve controls and procedural activities that can be implemented with respect to the existing design configuration.

APPENDIX C-3

FAILURE MODE, EFFECT AND CRITICALITY ANALYSIS (FMECA) PROCEDURE

APPROACH

The approach used to prepare the failure mode and effects analysis involves the tabulation of information on a standard work sheet. (See Figure C3-1) The numbers on the worksheet correspond to those given here which describe the worksheet entries:

(1) & (2) identification of the part or failure mode associated with that part.

(3) identification of the component effect resulting from that failure mode.

(4) identification of a system effects and severity factor based on the following:

Code No.	Severity Factor	Description
I	10	Most severe--crew safety jeopardized and mission aborted.
II	8	Mission aborted--safety hazard avoided with pilot skill.
III	5	Mission aborted--no safety hazard.
IV	5	Undesirable condition--flight can continue.
V	1	Operates normally, no effect.

(5) detectability of the failure mode by final test/inspection--a check mark (✓) indicates that failure mode is not detectable.

FMECA WORKSHEET

SYSTEM ________ COMPONENT ____________ PAGE ______ OF ______

DATE ____________

ENGR ____________

PART	FAILURE MODE	COMPONENT EFFECT	SYSTEM EFFECT	DETECT-ABILITY	FAILURE FREQUENCY	CRITICALITY
Hydraulic Pump	Leaky Pump	Loss of Hyd. Power	Flight Abort. (Precautionary)	----	----	----
Hydraulic By-Pass Solenoid	----	----	----	----	----	----
----	----	----	----	----	----	----
(1)	(2)	(3)	(4)	(5)	(6)	(7)

Figure C3-1

FMECA WORKSHEET

(6) frequency of the failure mode based on: M, λ ε t.

where:

P(x) = probability of failure mode

M = mode distribution

λ = part failure rate (from MTBF studies)

t = time (e.g., 2 hour mission)

Note: above parameters when combined are intended to express relative probabilities. Actual probabilities would include terms to reflect induced reliability and quality defects. This analysis assumes that these defects will not significantly vary on a part-by-part basis.

(7) criticality--the criticality ranking is derived from the formula $C = P(x) \times S$

where:

C = criticality

P(x) = probability of occurrence of the failure mode

S = the severity factor

APPENDIX C-4

PROCESS AND INSPECTION ANALYSIS PROCEDURE

PROCEDURE

Section 4.3.3.3 of this guidebook describes the overall background and methodology required to perform a process and inspection analysis for the purpose of estimating system reliability as it leaves production. As indicated previously, a process and inspection analysis involves the following steps:

(a) Define manufacturing process and inspection stations,

(b) Collect reject data,

(c) Estimate inspection efficiencies,

(d) Assess quality and reliability defect rates of manufacturing processes,

(e) Compute outgoing reliability defect rate.

This appendix provides an example of the implementation of the process and inspection analysis techniques given in Section 4.3.3.3.

To exemplify the technique, the rotor blade assembly process was chosen. The asembly process for the blade was shown in Figure 4-29 and is reproduced on the following page. To exemplify this analysis procedure, the following reject rate data, inspection efficiency factors and screening efficiency factors are assumed:

REJECT RATE DATA

Reject Rates

• Raw Material Inspection	1%
• Ultrasonic Inspection	5%
• Gage Inspection	5%
• Curing Cycle	5%
• Pull Test	2%
• Final Inspection	10%

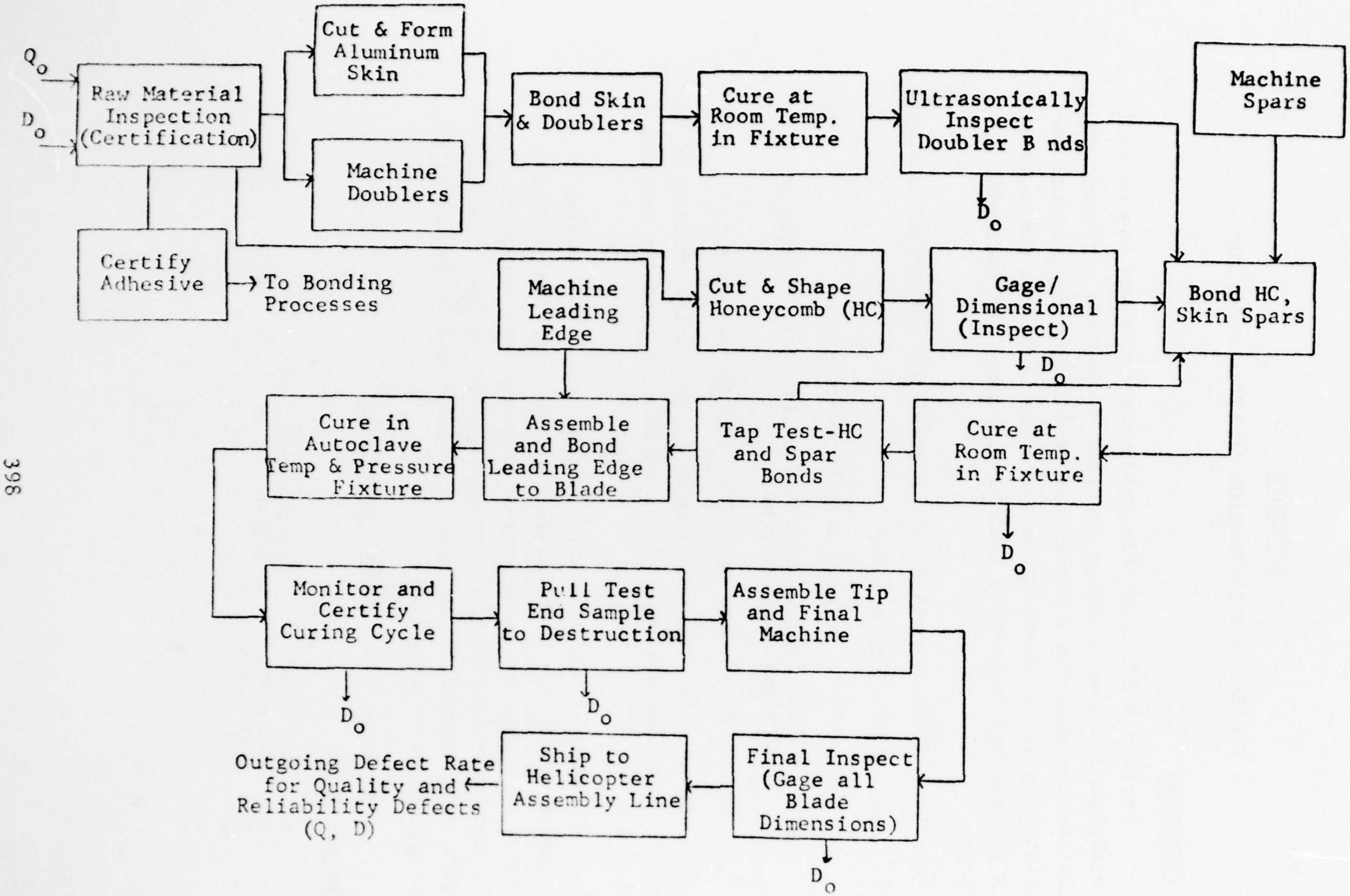


Figure C4-1 SIMPLIFIED FLOW CHART FOR ROTOR BLADE ASSEMBLY PROCESSES

INSPECTION/SCREENING EFFICIENCY FACTORS

Inspection	Inspection Efficiency	Screening Efficiency
• Raw Material	0.5	0.1
• Ultrasonic	0.6	0.1
• Gage/Dimensional	0.6	0.1
• Curing Cycle	0.6	0.1
• Pull Test	0.6	0.1
• Final Inspection	0.8	0.1

Using the reliability formula given by:

$$R(t) = \varepsilon^{-\lambda t}$$

and assuming that the failure rate and time are, respectively:

$$\lambda = 0.0007$$

$$t = 2 \text{ hrs}$$

leads to a value

$$R(t) = 0.9986$$

and

$$Q(t) \text{ (unreliability)} = 1-R(t) = 0.0014$$

This value reflects the inherent unreliability of the rotor blade calculated by conventional reliability techniques. This value of Q(t) along with an initial quality defect rate for each item of material are used in the process analysis to determine an equivalent MTBF. Calculations performed for each step of the assembly process leads to a final quality defect rate of 0.025 and a final reliability defect rate of 0.346. Assuming that 90% of the latent defects become actual failures during the first 100 hrs of operation and maintenance time, we find that the equivalent MTBF is approximatley 300 hrs.

Note, however, if we apply the screening program described in Section 4.3.3.3 and depicted in Figure B5-2, we find that the equivalent MTBF is approximately 2000 hours.

This means that the MTBF is improved sevenfold. This improved MTBF is based on incorporating screens at the following process points:

(1) Between steps for room temperature cure (machine spar) and tap test,

(2) Between room temperature cure (Bond Skin and Doublers) and ultrasonic inspection,

(3) Between final machining and bonding of tip to blade,

(4) At pull test.

In applying these screens, it is assumed that the screening strength efficiency is .8, and the screening inspection efficiency is .6.

	Failure Mode	MTBF	Cause	Screen
1)	Delamination of Spar to Skin	500	Poor Bond	Stress Cycle and Tap Test
2)	Delamination of Doublers	1000	Air Flow	Vibration (Low Cycle) and Ultrasonic
3)	Tip. Wt. Fitting Unbonding	500	Poor QC	Visual inspect for faulty bond
4)	Leading Edge to Blade Unbond			Sample Specimen Cured and Sectioned
5)	Tip Cover Cracking	500	Alternating Load	Vibration (Low Cycle) and Penetrant Test

Figure C4-2

ROTOR BLADE SCREENING PROGRAM

APPENDIX C-5

FAILURE REPORTING, ANALYSIS AND CORRECTIVE ACTION (FRACA)

DOCUMENTATION PROCEDURE

GENERAL

This appendix describes failure reporting, analysis and corrective action formats which are used as failure recurrence control documents during system development and production. These forms are particularly useful during growth or other development tests as detailed and permanent records of failure and corrective action experience. As retained experience, they can be used for subsequent development programs.

PROCEDURE

Suggested formats for failure reporting, analysis and corrective action suitable to accomplish the failure recurrence control functions are shown in Figures B6-1, 2 and 3. The following paragraphs describe the individual entries on each form and the manner in which they are completed. The circled numbers refer to the entry on the forms.

MALFUNCTION/FAILURE REPORT FORM

1 Report Number
Each report will have its own unique number. The use of preprinted numbers is recommended.

2 Date
The date to be inserted is the date on which the failure occurred.

3 Operating Time
The total operating time of the failed items will be entered. In cases where the failed item is part of a larger assembly or system, the operating time of the larger assembly will be entered.

4 & 5 System Name/Project Number
If the failure occurred during the conduct of system test or operation, the system name (or other identification) will be entered. Model numbers and serial

Malfunction/Failure Report		No. (1)	
System Name (4) Project Number (5)		Date of Occurence (2) Operating Time (3)	
Component Name (6) Comp No. (7) Serial No. (8)	Assembly Name (9) Assem. No. (10) Serial No. (11)		
Part Name (12) Part No. (13) Serial No. (14)	Repair Time ☐ Est. ☐ Actual Time Required (15) ☐ Hr. ☐ Min.		

CHECK ONE

☐ FAILURE DISCOVERED DURING DESIGN ENGINEERING (EXPLAIN)
(16)

☐ FAILURE DISCOVERED DURING SYSTEM/COMPONENT TEST
(17)

Test Procedure No.
Paragraph No.

TEST: A. ACCEPTANCE ☐ D. QUALIFICATION ☐
B. GROWTH ☐ E. OTHER ☐
C. DEVELOPMENT ☐

☐ FAILURE DISCOVERED DURING PRODUCTION
(18)

Test Procedure No.
Paragraph No.

A. TO PROD.CONT.FOR REPAIR ☐ PROD.ORD.NO.
B. SCRAP ☐
C. HOLD FOR MRB REVIEW ☐

SYMPTOMS OR DESCRIPTION OF MALFUNCTION/FAILURE
(19)

SIGNATURE (20)	DATE

PRELIMINARY INVESTIGATION
(21)

FAILURE CLASSIFICATION (22)	HUMAN INITIATED FAILURE ☐ (23)	
FURTHER ANALYSIS (24) REQUIRED YES ☐ NO ☐	(25) SIGNATURE	DATE
	APPROVAL	DATE

Figure C5-1 Failure Reporting Format

Failure Analysis Report	Reference Malfunction/ Failure Report No. (1)

Record of Parts/Components Analyzed

Part No. (2)	Mfg.	S/N	Date Code
Component No.	Mfg.	S/N	Date Code

Description of Analysis Approach, Techniques, Results & Conclusions
(Use Additional Sheets if Necessary)

(3)

Corrective Action to be Requested Yes☐ No☐ (4)	Signature ____________ (5)	Date ____________
	Approval ____________	Date ____________

Figure C5-2 Failure Analysis Format

Corrective Action Request	Reference Malfunction/ Failure Report No. (1)

To: ____(2)____ Dept. __________ Date of Request __________

Description of Problem

(3)

Recommended Action

(4)

Signatures ____________________ Date ______________

____________________ Date ______________

(5)

____________________ Date ______________

Action Taken (Describe)

(6)

ECN or ECP No. ____(7)____ Approval ____(8)____ Date ________

Follow-up Action Required (9) ☐ Yes ☐ No	Signatures ____(10)____ Date ________ ____________________ Date ________

Figure C5-3 Corrective Action Format

numbers will be entered here also. The impact of failure on system operation will be described under symptoms. The project number (if applicable) will be entered in the space provided.

6 thru 14 Component/Assembly/Part

If the failure occurred during the conduct of component or lower level test, the required information, applicable to the highest level will be entered. In addition, the description, part number and serial number of the specific failed item (depending on the level of replacement) will be entered as required. Symptoms pertinent to the item tested (e.g., component) will be entered in the space marked 19.

15 Repair Time

The time required to restore proper operation after failure will be entered in this space. The number of hours or minutes required for the repair plus an indication that the repair time entered is either an actual or estimated value.

16, 17 & 18 Failure Discovered During....

The originator of the failure report will compete one of these three blocks depending on the test/operation being conducted, whether the failure occurred during formal test, whether failure occurred during production, etc. Where test procedures are used for formal test, the procedure number and applicable paragraph number will be entered.

19, 20 & 21 Symptoms/Signature/Preliminary Investigation

The originator of the report will describe briefly the synptoms of the malfunction in the space provided. Reference to the test procedures should be made where applicable. The initiator of the report will sign and date the form in the space provided.

The results of a preliminary investigation to determine the nature and cause of the failure and also the necessity for further analysis will be described. The results of this preliminary investigation will be described in Block 21.

22 Failure Classification

Failures will be classified as either significant or non-significant. In general, significant failures are defined as those which may cause one of the following:

(a) Delay the development and/or delivery of the equipment,
(b) Require a change in parts used,
(c) Require a part improvement program,
(d) Require a change of part vendor,
(e) Require a design change,
(f) Cause suspicions that the failure is not random (i.e., prior failures of the part under similar conditions and environments have occurred),
(g) Require an assembly or process change,
(h) Require a change in inspection procedures.

23 Human Initiated Failure
This box shall be checked only if there is definite knowledge that the failure was caused by human error.

24 Further Analysis Required
Check appropriate box.

25 Signature/Approval
Normally, the person who conducts the preliminary investigation, classifies the failure and indicates the necessity for further analysis will sign and date the form. Space for an approval signature is provided.

FAILURE ANALYSIS REPORT FORM

1 Reference Failure Report Number
The original failure report number will be entered in this space.

2 Record of Parts/Components Analyzed
The part numbers, component numbers, manufacturer's, serial numbers and date codes relative to the item analyzed will be entered in this space.

3 Analysis
In this portion of the form, the Reliability Analyst will describe the results of the analysis. All pertinent part identification data (serial number, date code, etc.) will be entered in this space. The analysis will list the cause of failure insofar as is possible. Consideration shall be given to applicable methods of failure analysis including test, X-rays, dissection, chemical analysis, microphotography, etc. In addition, the analysis will show any secondary failures caused by the primary failure.

4 Corrective Action to be Requested
Depending upon the results of analysis, this block shall be checked either yes or no.

5 Signature/Approval
The failure analyst will sign and date the form in the space provided. An approval signature is also required.

CORRECTIVE ACTION REQUEST FORM

1 Reference Failure Report No.
The original failure report number will be entered in this space.

2 Addressee
The person requested by the originator to take action along with his departmental function will be entered. The date the corrective action request is initialed will be written in the space provided.

3 & 4 Problem Description/Recommended Action
Based on the results of failure analysis, the description of the problem to be corrected and the recommended action will be listed here. Pertinent additional data will be attached to the form as required.

5 Signatures
Signatures of the originator, failure analyst, manager or other personnel involved in formulation of the corrective action recommendations will be entered in this space.

6 Action Taken
The addressee will describe the action taken or to be taken in response to the identified problem.

7 ECN or ECP No.
In the event that Engineering Change Notice (ECN) or Engineering Change Proposals (ECP) are associated with or are required for implementation of the corrective action, the appropriate cross referencing number will be entered in this space.

8 Approval
The person who approves the action to be taken will sign the form in space 8. The completed form containing action taken will be returned to the originator.

9 & 10 Follow-up Action & Signatures

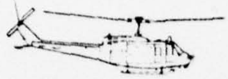
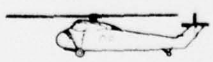
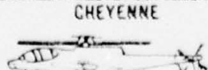
The originators of the form will determine the necessity for follow-up action and mark the appropriate box. Final signatures will indicate concurrence with the action taken.

Appendix D

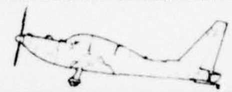
DESIGNATION OF ARMY AIRCRAFT

DESIGNATION OF ARMY AIRCRAFT

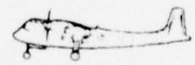
HELICOPTER SERIES

DESIGNATION	ENGINE	POPULAR NAME
AH-1G	T53-L-13/A/B	COBRA 
TH-1G	T53-L-13/A/B	
UH-1A	T53-L-1A	IROQUOIS 
UH-1B	T53-L-9A,11/B/C/D	
UH-1C	T53-L-11/B/C/D	
UH-1D	T53-L-9A,11/B/C/D	
UH-1H	T53-L-13/A/B	
UH-1M	T53-L-13/A/B	
OH-6A	T63-A-5A	CAYUSE 
OH-13K	6VS-335A	SIOUX 
OH-13S	0-435-25A	
TH-13T	0-435-25A	
OH-23B	0-335-5D	RAVEN 
OH-23C	0-335-5D	
OH-23D	0-435-23C	
OH-23G	0-540-9A	
CH-34C	R-1820-84C	CHOCTAW 
VH-34C	R-1820-84D	
CH-47A	T-55-L-5,7	CHINOOK 
CH-47B	T55-L-7/B/C	
CH-47C	T55-L-7C,11A	
CH-54A	T73-P-1	TARHE 
CH-54B	T73-P-700	
TH-55A	HIO-360B1A	OSAGE 
AH-56A	T64-GE-716	CHEYENNE 
OH-58A	T63-A-700	KIOWA 

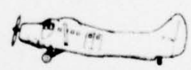
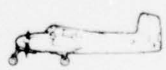
OBSERVATION SERIES

DESIGNATION	ENGINE	POPULAR NAME
O-1A	0-470-11B	BIRD DOG 
O-1G	0-470-11B	
TO-1A	0-470-11B	
TO-1E	0-470-11B	
YO-3A	IO-360-D	

VTOL AND STOL SERIES

DESIGNATION	ENGINE	POPULAR NAME
OV-1A	T53-L-7,7A	MOHAWK 
OV-1B	T53-L-7,7A	
OV-1C	T53-L-7,7A,15	
OV-1D	T53-L-701	

UTILITY SERIES

DESIGNATION	ENGINE	POPULAR NAME
U-1A	R-1340-61	OTTER 
RU-1A	R-1340-61	
U-6A	R-985-AN-39/A	
	R-985-AN-39/A	
U-8D	0-480-1A,1B	SEMINOLE 
RU-8D	0-480-1A,1B	
U-8F	0-480-3,3A	
U-8G	0-480-1A,1B	
U-9C	GSO-480-B1A6	AERO COMMANDER 
YU-9	GO-435-C2B1	
U-10A	GO-480-G1D6	COURIER 
U-21A/G	T74-CP-700	UTE 
RU-21A	T74-CP-700	
RU-21B	T74-CP-702	
RU-21C	T74-CP-702	
RU-21D/E	T74-CP-700	
U-21F	PT6A-28	

TRAINER SERIES

DESIGNATION	ENGINE	POPULAR NAME
T-41B	IO-360-D	MESCALERO 
T-42A	IO-470-L	COCHISE 

PREPARED BY:
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